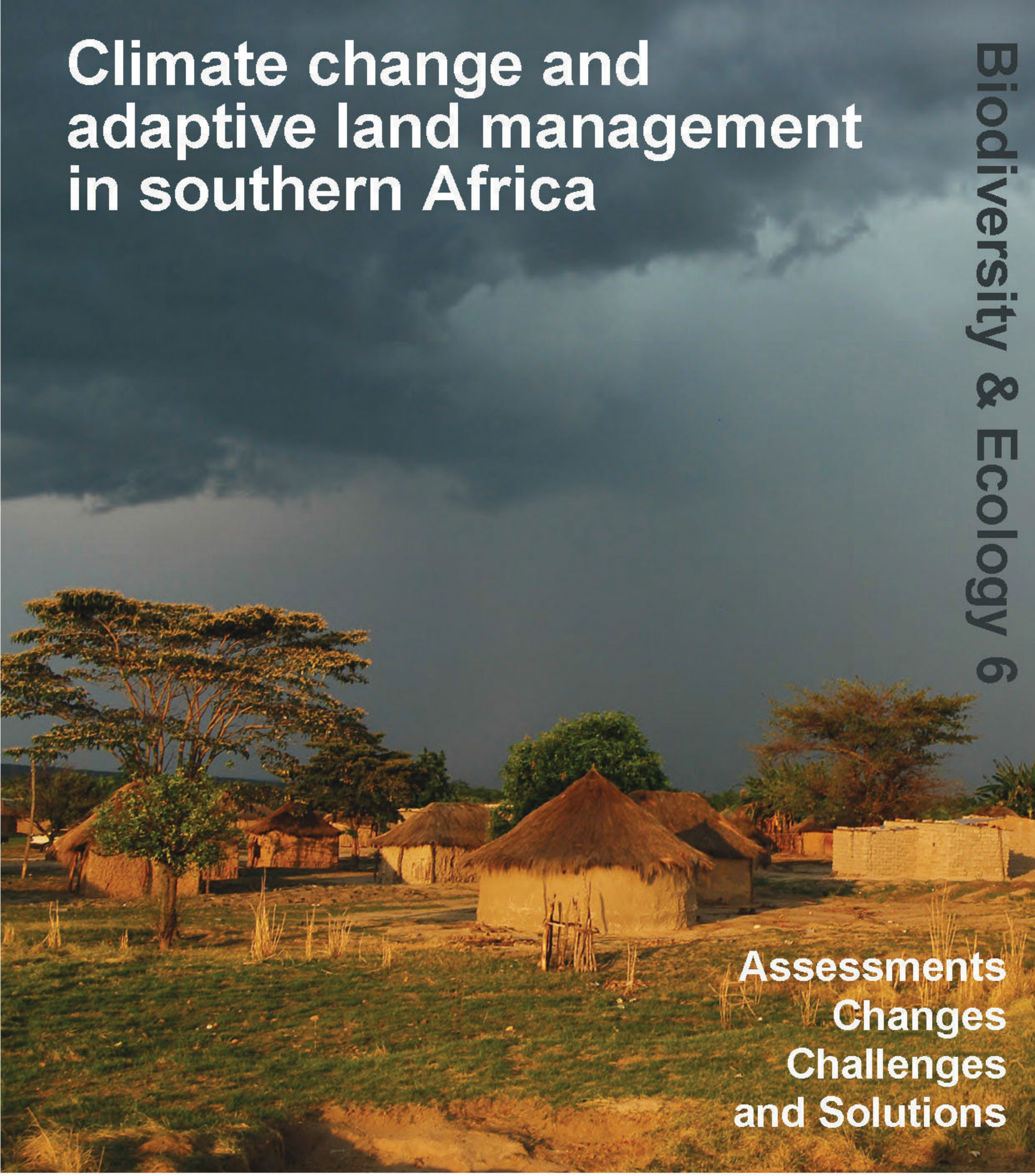
Climate change and adaptive land management in southern Africa

Biodiversity & Ecology 6



Assessments
Changes
Challenges
and Solutions

Product of the first research portfolio of

SASSCAL 2012–2018

Southern African
Science Service Centre for
Climate Change and
Adaptive Land Management

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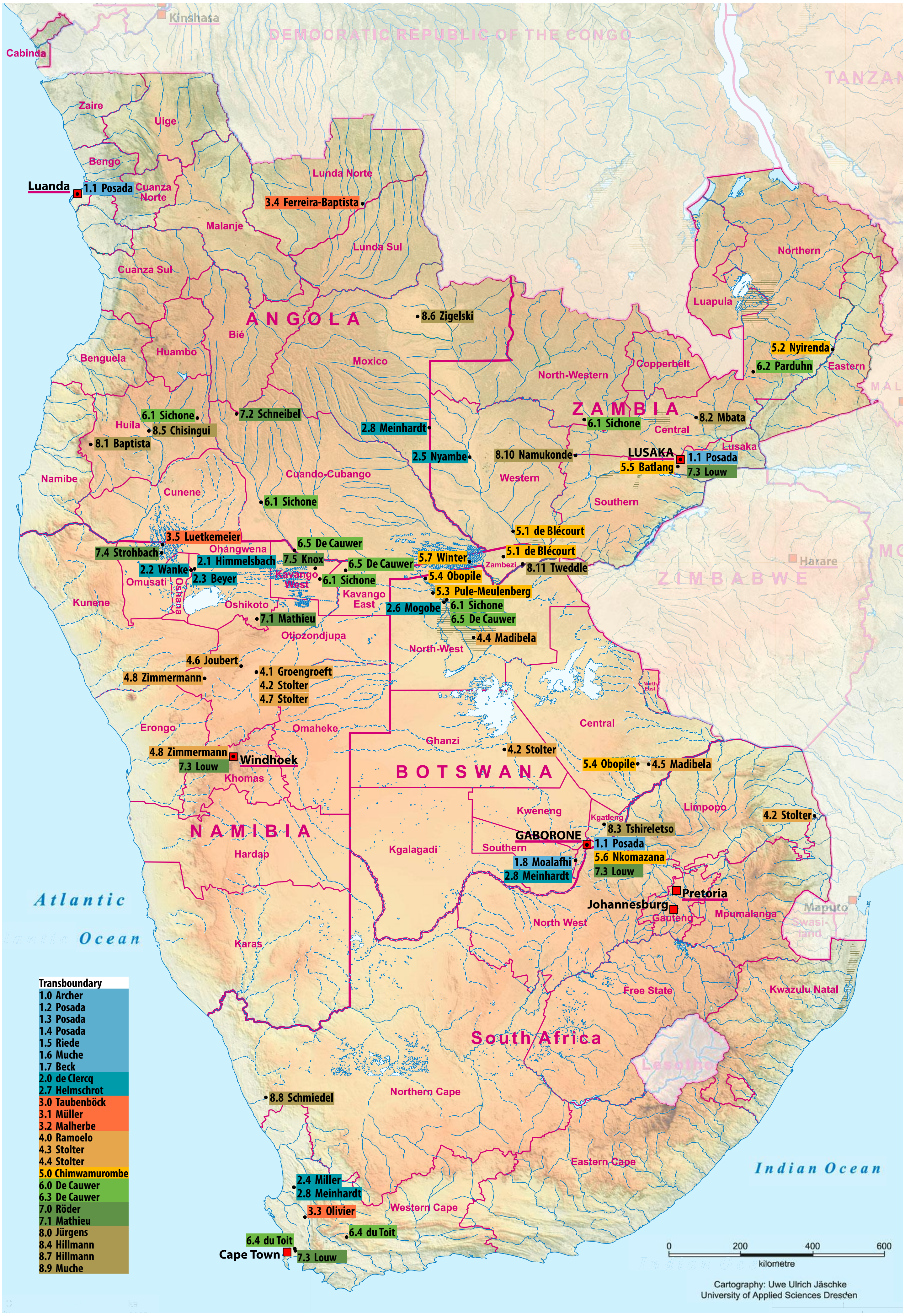

Kinshasa
DEMOCRATIC REPUBLIC OF THE CONGO
TANZANIA
Cabinda
Zaire
Uige
Bengo
Luanda
1.1 Posada
Cuanza Norte
Lunda Norte
3.4 Ferreira-Baptista
Malanje
Lunda Sul
Cuanza Sul
ANGOLA
8.6 Zigelski
Bié
Huambo
Benguela
Moxico
Northern
Luapula
5.2 Nyirenda
6.2 Parduhn
Eastern
Copperbelt
North-Western
ZAMBIA
6.1 Sichone
7.2 Schneibel
8.5 Chisingui
Huíla
8.1 Baptista
2.8 Meinhardt
8.2 Mbata
6.1 Sichone
Central
2.5 Nyambe
8.10 Namukonde
LUSAKA
1.1 Posada
5.5 Batlang
7.3 Louw
Lusaka
Namibe
Cuando-Cubango
Western
Southern
Cunene
6.1 Sichone
5.1 de Blécourt
3.5 Luetkemeier
6.5 De Cauwer
5.1 de Blécourt
7.4 Strohbach
Ohangwena
7.5 Knox
5.7 Winter
Zambezi
8.11 Tweddle
2.2 Wanke
2.1 Himmelsbach
6.5 De Cauwer
Harare
Omusati
2.3 Beyer
Kavango West
6.1 Sichone
5.4 Obopile
ZIMBABWE
Oshana
5.3 Pule-Meulenberg
Kunene
Oshikoto
Kavango East
2.6 Mogobe
6.1 Sichone
7.1 Mathieu
6.5 De Cauwer
Otjozondjupa
4.4 Madibela
North-West
4.6 Joubert
4.1 Groengroeft
4.8 Zimmermann
4.2 Stolter
4.7 Stolter
North East
Erongo
Omaheke
Central
Ghanzi
4.2 Stolter
4.8 Zimmermann
Windhoek
5.4 Obopile
4.5 Madibela
7.3 Louw
BOTSWANA
Khomas
Kweneng
Limpopo
Kgatleng
4.2 Stolter
NAMIBIA
8.3 Tshireletso
GABORONE
Kgalagadi
Southern
1.1 Posada
Hardap
1.8 Moalafhi
5.6 Nkomazana
2.8 Meinhardt
7.3 Louw
Pretoria
Atlantic Ocean
Johannesburg
Gauteng
Mpumalanga
Maputo
Swaziland
North West
Karas
Free State
Kwazulu Natal
Transboundary
1.0 Archer
1.2 Posada
1.3 Posada
1.4 Posada
1.5 Riede
1.6 Muche
1.7 Beck
2.0 de Clercq
2.7 Helmschrot
3.0 Taubenböck
3.1 Müller
3.2 Malherbe
4.0 Ramoelo
4.3 Stolter
4.4 Stolter
5.0 Chimwamurombe
6.0 De Cauwer
6.3 De Cauwer
7.0 Röder
7.1 Mathieu
8.0 Jürgens
8.4 Hillmann
8.7 Hillmann
8.9 Muche
South Africa
Lesotho
8.8 Schmiedel
Northern Cape
Eastern Cape
Indian Ocean
2.4 Miller
2.8 Meinhardt
3.3 Olivier
Western Cape
6.4 du Toit
6.4 du Toit
Cape Town
7.3 Louw
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400
600
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Climate change and adaptive land management in southern Africa

Assessments, changes, challenges, and solutions

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Foreword

Dr Jane M Olwoch, SASSCAL Executive Director

Climate change and long-term environmental changes are linked in space and time. Temporal changes in the physical and social environment are behind the gradual increase in greenhouse gases since industrial times. The increase in population and spatial connectivity of people, places, and the planet has itself resulted in the exploitation of natural resources beyond local borders. The connectivity of ecosystems and services through energy flow and material exchange through the biosphere, atmosphere, lithosphere, and hydrosphere means that we live in shared spaces in which the biogeochemical cycles are at our disposal to maintain or change for the better or worse. Even without climate change, biogeochemical cycles have been altered by human activities beyond their capacity to come back to their natural states. It is well established that human activities through various types of land use and cover changes have altered the natural composition of nitrogen, phosphorus, and sulfur and further directly or indirectly influenced the climate system. Superimposed on the current and future projected climate change, changed biogeochemical cycles are already increasing the vulnerability of biodiversity, food security, water security, forests and woodlands, and human and animal health to climate change. The Intergovernmental Panel on Climate Change's fifth assessment report (2014) highlighted that as temperatures continue to rise and precipitation declines across many areas in Africa, ecosystems are already being affected by climate change, and future impacts are expected to be substantial. The report further states that such changes include shifting ranges of some species and ecosystems as a result of elevated carbon dioxide (CO_2) and climate change, beyond the effects of land use change and other non-climate stressors. The effects of climate change on water resources are also reported with high confidence, as are impacts on food security in particular through the reduction in cereal production. Southern Africa continues to experience prolonged droughts, with the 2015 agricultural season in southern African being considered the driest in 35 years, leading to a deficit of 9.3 million tons in cereal crop harvests, among others.

To address such complex and cross-regional environmental and social challenges, a regionally integrated approach provides the most reliable and financially sustainable mechanism. SASSCAL's value proposition centers around regional integration, relevance, transdisciplinary research, and institutional cooperation and partnerships. The four-pillar value proposition also provides a framework in which future research, service production, and capacity-building programmes will be conducted. Furthermore, SASSCAL's mission is to strengthen the regional capacity to generate and use scientific knowledge products and services for decision making on climate change and adaptive land management through research management, human capital development, and service provision. To achieve this, quality climate and long-term environmental data must continuously be collected by way of demand-driven research. Similarly, support tools and research capacities must be developed, and the information derived must be made accessible to stakeholders. This ensures that the role of science is understood and mainstreamed in national and regional policy-making institutions through the production of services that are needed to strengthen adaptation and mitigation strategies. SASSCAL's research portfolio 1.0 outcomes from 88 research tasks are a vivid manifestation of the role of research in contributing to the region's research outputs and knowledge economy.

This book provides a comprehensive collection of research outputs, data infrastructure, tools, and capacity-building outcomes from SASSCAL's research portfolio 1.0. This book also signifies an entry into the future in which SASSCAL supported research continues unabated and anchored by the establishment of SASSCAL as an institution and successes from the SASSCAL 1.0 portfolio in terms of research outputs, services, and the research infrastructure. In addition, several strategic partnerships created in the region and abroad position SASSCAL as a sustainable institution that will guarantee long-term availability of knowledge and data; hosting of long-term data is a fundamental base to detect and understand changes over time and space.

It has been a long but fulfilling journey that has been enabled by strong collaboration between Angola, Botswana, Germany, Namibia, South Africa, and Zambia. Congratulations to all the researchers and students who have produced such quality products. Much deserved appreciation to all research and academic institutions that took part in the process. Special thanks go to the Federal Ministry of Education and Research (BMBF), which provided financial and technical support for the SASSCAL portfolio 1.0 and production of this book.

Jane M Olwoch

About the book: An introduction

Dr Rasmus Revermann

This book showcases research results obtained during the SASSCAL research portfolio 1.0 from the years 2012–2018. It offers assessments of the region's values and resources, gives information on the direction and intensity of environmental changes, and evaluates the risks and challenges involved. Further, it proposes pathways towards improved management tools and instruments for climate change adaptation and sustainable land management.

The SASSCAL Research Portfolio 1.0

The scoping process organised during the initial phase of SASSCAL was a large bottom-up, participatory process. It brought together a very wide range of stakeholders from all involved countries: Angola, Botswana, Germany, Namibia, South Africa, and Zambia. The aim was to create a robust joint vision of the most important research needs and to identify achievable research approaches within a regionally integrated portfolio. Interestingly, all African countries involved developed similar views regarding the most important needs and demands, in part based on pre-existing National Development Plans. The most important decision was to unpack what began initially as three main thematic areas—'Climate', 'Water', and 'Land'—into the final five thematic areas: 'Climate', 'Water', 'Forestry', 'Agriculture', and 'Biodiversity'. At the same time, almost all countries voted for a broad call for bottom-up proposals from local research institutions. This initiated a team spirit among the researchers involved that still guides and supports the activities today.

The book structure

Some of the fruits of this five-year-long journey are presented in this book. It is structured according to thematic key areas. To allow a deeper exploration of these huge thematic complexes, the five thematic areas of SASSCAL have been arranged in eight thematic chapters: 1. Climate, 2. Water resources, 3. Risk management, 4. Rangelands, 5. Food security, 6. Forest resources, 7. Land cover dynamics, and 8. Biodiversity. The first article of each chapter introduces the topic, gives an overview of recent findings in the respective areas, and defines common concepts. The subsequent articles present original research findings of the SASSCAL tasks. Infoboxes add to this by providing summaries of certain aspects or by presenting newly developed (software) tools or databases, amongst other supplements.

We hope to present a book that offers scientific information for a wide audience and that is also useful for both interested stakeholders and scientists from other disciplines. As such, the articles do not focus on details of the applied methodology, but instead concentrate on the relevant outcomes. However, references to more detailed descriptions of how the studies were done or how the data were analysed are provided. In order to ensure high scientific quality, all articles underwent a peer-review process in which all articles were checked by two experts in the field. This iterative process clearly improved both the clarity and quality of the submitted papers.

The content of the book

Long term monitoring and data availability

Research on climate change and adaptive land management requires a strong data foundation to come to scientifically sound conclusions, upon which recommendations for management can be based. However, in many areas, appropriate data is scarce or unavailable, or the necessary lengths of time series are not given. Thus, various tasks addressed these shortcomings in the different thematic areas. As such, a huge success of the first years of SASSCAL was the implementation of the SASSCAL WeatherNet, involving the installation, maintenance, and online database creation of 154 automatic weather stations [1.6]; how the newly gathered data can be used for improved water management is illustrated in [1.8] and various other studies make use of climate data produced by the WeatherNet. The scope of the activities in the thematic area 'Climate' also included reactivating and archiving historic climate data [1.1]. Looking a step ahead, the new SEACRIFROG initiative is presented [1.7], which will embed SASSCAL initiatives in the global research context on climate change. For an excellent review of how climate change may affect southern Africa, refer to the overview article climate [1.0].

Similarly to climate change studies, research on biodiversity also requires long time series to monitor changes and the factors inducing these changes. This need led to the establishment of a network of biodiversity observatories that has become a crucial research infrastructure [8.0]. The network has been continued and expanded in SASSCAL 1.0. and data on the 57 Biodiversity Observatories can be found online in the SASSCAL ObservationNet [8.7]. Article [8.8] provides very detailed insight into the temporal changes of the vegetation at the Soebatsfontein Observatory based on 17 years of annual monitoring and nicely illustrates the value of long-term ecological time series data. In [8.6], first insights into the functioning of the social-ecological systems of the newly established Cameia National Park Observatory are presented. An important function of SASSCAL for the future will be the storage of data and making data sets available for future research in the SASSCAL Information and Data Portal [2.7].

Water quantity and quality above and below ground

The recent water crisis in southern Africa has made the general population very aware of the immense value of water. The overview article [2.0] nicely summarises the activities carried out in the thematic area 'Water' and highlights perspectives for better management. Similarly, the subsequent article [2.1] reviews the activities dealing with groundwater research in southern Africa and focuses particularly on the inspiring discovery of semi-fossil, deep aquifers in northern Namibia and southern Angola. Following up on this topic, [2.2] provides an in-depth analysis of water quality and the available water sources on the local level in the Cuvelai-Etosha Basin. In the same region, the vulnerability to drought on the household level was investigated [3.5]. Studies on water quality were also carried out in wetland ecosystems that remain rather pristine: the Barotse floodplain in Zambia [2.5] and the Okavango Delta [2.6]. These studies collected baseline data to monitor potential impacts of developments in the upper reaches of each region. Examples of how hydrological modelling tools can be used to provide support for management decisions are given in the studies presented in [2.4] and [2.8].

Management risks

A conceptual approach to risk management and the corresponding terminology are provided in the overview article, [3.0]. The subsequent articles deal with different phenomena related to 'risks', such as floods and droughts [3.1]; present an index for extreme climate events [3.2]; and investigate presumably inactive gully systems in the Swartland region of South Africa [3.3]. A topic often overlooked, with hardly any scientific coverage, is the impact of mining in remote northeast Angola. The study presented in [3.4] mapped the impacts of both artisanal and industrial mining activities in the border region to the Democratic Republic of Congo, spotlighting their dramatic effects on the ecosystems.

Providing food and maintaining ecosystem services

In most parts of southern Africa, smallholders are the backbone of food security. However, yields are often far below the land's potential and in some cases are even declining [5.0]. The agriculture tasks in the SASSCAL 1.0 research portfolio have explored new and sometimes unconventional ways of closing the yield gap, such as using rhizobia as biofertilizer [5.3] or making use of legumes for intercropping [5.4]. Similarly, wild legumes have been analysed for their forage quality and their potential is discussed as supplementary foods in rangelands for times when other available food sources for herbivores are not available [4.2, 4.3 and 4.5]. To aid adaptation to increasing droughts and shortened growing seasons due to climate change, germplasm of landraces of maize and cowpea has been evaluated [5.5] and drought-resistant varieties were identified [5.6]. The conflict between land use and wild animals is examined in a Game Management Area in eastern Zambia and solutions on the farm level discussed [5.2]. As pointed out in article [5.7], a holistic approach to landscape management is needed to reconcile food security on the one side and conservation needs on the other.

In the rangelands of the semi-arid areas of southern Africa, bush encroachment and erosion are severe problems affecting large areas, negatively impacting the carrying capacity for wild and domestic herbivores [4.0 and 4.7]. The study in [4.1] presents a long time series of monitoring soil water content in cleared and bush encroached sites. The authors are able to show the differences in ground water recharge which is negatively related to the woody cover above ground. In [4.8] the authors give food for thought on how rangelands can be rehabilitated using simple methods requiring landscape literacy and material available in the surrounding area.

Fire

Disaster and tool at the same time, fire is an omnipresent feature of many landscapes in southern Africa and can have a profound impact on ecosystems. Various studies presented in the book address this topic. The impact of fire on small mammal communities is investigated in the Busanga Swamps in Zambia [8.10]; [6.5] examines its effect on the structure and composition of the Baikiaea woodlands. A study of different fire treatments on the Waterberg analyses the impacts on various organismic groups such as insects, large herbivores, and plants, as well as on soil properties [4.6]. In the overview article on land cover dynamics, the observation of spatial and temporal fire patterns using satellite imagery is discussed [7.0].

Woodland ecosystems and their usage

The more mesic parts of southern Africa—appearing mainly in the countries of Angola and Zambia, but also the northern parts of Namibia and Botswana and, to some extent, in northeastern South Africa—are covered by dry tropical forests and woodlands [6.0]. While they provide livelihoods and important ecosystem services to a large population, deforestation and forest degradation due to charcoal production [7.2] and agricultural expansion [6.2] is advancing. The conversion of woodlands to agricultural area leads to a reduction of organic carbon and nutrients in the soil [5.1].

The dry tropical forest and woodland biomes have received much less attention in scientific studies than the tropical rainforests. Forest inventories are indispensable for understanding these woodland ecosystems. Based on data recorded on vegetation plots and in forest inventories, the spatial patterns of above-ground biomass and its environmental drivers were investigated [6.1]. Furthermore, the 'Biodiversity' chapter presents two studies investigating spatial patterns of vegetation composition, one in the Katleng District, Botswana [8.3], and the other in Huíla Province, Angola [8.5].

Moreover, the 'Forest Resources' chapter has much to offer on how to better manage woodland resources. As such, the impact of fire on woodlands is discussed [6.5] and findings are presented on how native tree species, including several of interest as timber species, can be propagated [6.3]. An economic analysis on the return from forest farm lots is provided [6.6], showing that these can be economical even on marginal sites. A good example of how to integrate perspectives from very different disciplines is presented in article [6.2], in which the authors combine ground-based anthropological studies with remote sensing data and discuss perceptions of deforestation in Zambia.

The bird's eye perspective

The chapter 'Land Cover Dynamics' will be of interest to many scientists and stakeholders alike; here, authors with different disciplinary backgrounds showcase how remote sensing technology can be used to monitor social-ecological systems and to detect occurring changes. The overview [7.0] presents analyses based on the full Landsat archive for the SASSCAL region and showcases several applications based on other types of satellite imagery—a great source of inspiration for researchers from all disciplines. In the following articles, the use of new techniques is presented and used to illustrate how they can facilitate monitoring of woodlands in the future: airborne LiDAR data can be combined with satellite imagery to estimate woody cover of large areas [7.1], and unmanned aerial vehicles (UAVs) can aid very detailed analysis of woodland cover and structure on the local scale [7.4 and 7.5].

Biodiversity

Southern Africa harbours an enormous diversity—much of it still barely documented. Within SASSCAL, several studies aimed at closing this knowledge gap. While [8.1] documented the herpetofauna at one particular area on the Angolan escarpment, finding new species never documented in the country before, [8.2] compiled a comprehensive checklist of the cockroach and termite species to be found in Zambia. The concluding article of the book, [8.11], tells the story of Lake Liambezi and its rise and fall as a hub of fish diversity and fisheries. Subsequent years of high rainfall led to the filling of the lake and gave rise to large fish stocks. However, as the waters receded a few years later, both fish populations and, consequently, the fisheries collapsed again. The detailed observations allowed the authors to derive concrete recommendations for better management for the next time Lake Liambezi starts to refill.

Capacity development

Finally, we have two contributions that illustrate a very important pillar of the SASSCAL approach: capacity development. In two short contributions, two newly established master's courses at universities in the SASSCAL region are presented, filling important gaps in the academic curricula: one on dryland forestry [6.4] and the other on remote sensing [7.3].

Further reading

Obviously, not all outcomes of such a large initiative such as SASSCAL can fit in one volume. Thus, we included a 'further reading' section at the end of the book where information regarding further studies produced by SASSCAL, many of them freely available online, can be found. This section also contains a list of the numerous theses that have been completed in the context of SASSCAL.

General acknowledgements

The production of this book was a huge team effort. First of all, we would like to thank all the contributing authors, more than 200 in total, for sharing their results and findings, and for preparing the contributions of this book. Scientific work is often labour intensive, and thus we would like to express our gratitude to all people involved in gathering data in the field or in the lab, students, staff and local field assistants alike. An important part of scientific writing is getting feedback from colleagues. As such, we are indebted to the many reviewers who provided their input and valuable comments, which improved the manuscripts notably. We also would like to thank the principal investigators who initially designed the research tasks. Furthermore, we are grateful for all the logistical support that was continuously provided by the staff of the Regional Secretariat of SASSCAL and the National Nodes of the involved countries.

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The editorial team: Rasmus Revermann, Kristin M. Krewenka, Ute Schmiedel, Jane M. Olwoch, Jörg Helmschrot, and Norbert Jürgens

Climate

Seasonal prediction and regional climate projections for southern Africa

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Abstract: Temperatures over southern Africa have been increasing rapidly over the last five decades, at a rate of about twice the global rate of temperature increase. Further drastic increases, in the order of 6°C by the end of the century relative to the present-day climate, may occur over the central and western interior regions under low-mitigation futures. Moreover, southern Africa is projected to become generally drier under low-mitigation climate change futures. Such changes will leave little room for adaptation in a region that is already characterised as dry and hot. Impacts on crop and livestock farming may well be devastating, and significant changes may occur in terms of vegetation cover in the savannas, particularly in the presence of human-induced land degradation. Under modest to high mitigation, southern Africa will still experience further climate change, but amplitudes of change will be reduced, potentially leaving more room for adaptation. Skilful seasonal forecasts may become an increasingly important adaptation tool in southern Africa, especially when combined with a robust weather station monitoring network.

Resumo: A temperatura no Sul de África tem vindo a aumentar rapidamente ao longo das últimas cinco décadas, a uma taxa de cerca do dobro da global. Aumentos adicionais drásticos, na ordem dos 6°C até ao final do século em relação ao clima actual, poderão ocorrer nas regiões interiores centrais e ocidentais sob cenários futuros de baixa mitigação. Além disso, prevê-se que o Sul de África irá tornar-se geralmente mais seco sob cenários futuros de baixa mitigação das alterações climáticas. Tais alterações deixarão pouco espaço para a adaptação numa região que já é caracterizada como seca e quente. Os impactos na agricultura e na pecuária poderão ser devastadores, e alterações significativas poderão ocorrer em termos de cobertura vegetativa nas savanas, particularmente na presença de degradação da terra induzida pelo Homem. Com uma mitigação média-alta, o Sul de África continua influenciado pelas alterações climáticas, mas as amplitudes são reduzidas, deixando potencialmente mais espaço para a adaptação. Previsões sazonais competentes poderão tornar-se numa ferramenta de adaptação cada vez mais importante no Sul de África, especialmente quando combinadas com redes robustas de monitorização por estações meteorológicas.

Climate

Introduction

The past few years in southern Africa (in both the summer and winter rainfall regions) have demonstrated yet again the vulnerability of the subcontinent to climate variability. Multi-year below-normal summer rainfall has had a severe impact on key sectors, including agriculture and water, as have multiple more recent winters with below-normal rainfall (see, for example, Archer et al., 2017).

Such conditions have highlighted the need for climate science in the region that truly enables us to both predict conditions of climatic risk in the shorter to the longer term and to use such information to improve short- and long-term readiness (Winsemius et al., 2014). In this overview article, we describe work in climate prediction undertaken on both longer-term climate change projections and seasonal early warning. We conclude by a brief discussion of the essentials beyond climate science, where we may potentially effectively translate information into real utility.

Projections of future climate change over southern Africa

Later in this chapter, we consider climate observations and data availability; and it should be noted at the start of discussing the latest findings in terms of climate change projections for the continent that observation and data gaps remain a significant concern. Observed data also constrain our work in the area of seasonal forecasting and early warning (see section to follow). Figure 4, for example, shows the uneven coverage of observed climate data for the continent, particularly outside of South Africa. That limitation notwithstanding (and we provide more detail later in the chapter), substantive work has been undertaken in terms of climate change projections on the continent. Climate change is projected to have widespread impacts in southern African during the 21st century, particulalrly under low-mitigation futures (Niang et al., 2014). Temperatures are projected to rise rapidly, at 1.5 to 2 times the global rate of temperature increase (James & Washington, 2013; Engelbrecht et al., 2015). Indeed, the observed rate of temperature increase is particularly high over the interior regions of southern Africa. Here temperature trends as high as a 2 to 3.6°C increase per century have been recorded over the period 1961–2010 (Engelbrecht et al., 2015; Kruger & Sekele, 2013). In addition to the projected increases in surface temperature, the southern African region is also projected to become generally drier under enhanced anthropogenic forcing (Christensen et al., 2007; Engelbrecht et al., 2009; Haensler et al., 2010, 2011; James & Washington, 2013; Niang et al., 2014). These regional changes will plausibly have a range of impacts in southern Africa, including impacts on energy demand (in terms of achieving human comfort in buildings and factories), agriculture (e.g., reductions of yield in the maize crop under higher temperatures and reduced soil moisture; Landman et al., 2017), livestock production (e.g., higher cattle mortality as a result of oppressive temperatures), water security (through reduced rainfall and enhanced evapotranspiration; Engelbrecht et al., 2015) and human health (through oppressive temperatures; Garland et al., 2015).

Moreover, climate change is to take place not only through changes in average temperature and rainfall patterns, but also through changes in the attributes of extreme weather events. For the southern African region, generally drier conditions and the more frequent occurrence of dry spells are plausible over most of the interior (Christensen et al., 2007; Engelbrecht et al., 2009; Haensler et al., 2011). Tropical cyclone tracks are projected to shift northward, bringing more flood events to northern Mozambique and fewer to the Limpopo province in South Africa (Malherbe et al., 2013). Cut-off low related flood events are also projected to occur less frequently in South Africa (e.g., Engelbrecht et al., 2013) in response to a poleward displacement of the westerly wind regime. Intense thunderstorms plausibly may occur more frequently over South Africa in a generally warmer climate (e.g., Engelbrecht et al., 2013). Perhaps most important is that the regional changes in circulation that are plausible over southern Africa, in particular an increase in the frequency and intensity of mid-level high-pressure systems, may plausibly induce the more frequent occurrence of heat-wave events over the region (e.g., Engelbrecht et al., 2015; Garland et al., 2015).

It is against this background that a focused effort was made to further explore the climate change futures of southern Africa through a coordinated SASSCAL research programme, in addition to other research active in the subcontinent and on the continent more broadly. At the CSIR in South Africa and at the Climate Service Center Germany (GERICS), the most recent global circulation model (GCM) projections of the Coupled Model Intercomparison Project Phase Five (CMIP5) and Assessment Report Five (AR5) of the Intergovernmental Panel on Climate Change (IPCC) were downscaled to 50 km resolution over Africa. These simulations are for the period 1961 to 2100, follow the experimental design recommended by the Coordinated Downscaling Experiment (CORDEX), and have been derived for low- (Representative Concentration Pathway 8.5 [RCP8.5]), modest-high- (RCP4.5) and high-mitigation (RCP2.6) scenarios. The data of these simulations are also made available to the international science community via the CORDEX databases. The regional climate model used at the CSIR is the conformal-cubic atmospheric model (CCAM), a variable-resolution global climate model (GCM) developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (McGregor, 2005). At GERICS the simulations have been conducted with the REMO regional climate model. For each of the RCPs, six different GCMs were downscaled, so that the results presented below are based on an ensemble of possible future developments. The CCAM simulations were performed on supercomputers at the Centre for High-Performance Computing (CHPC) of the Meraka Institute of the CSIR in South Africa; the REMO simulations were conducted at the German Climate Computing Center in Hamburg, Germany.

The CCAM projected changes in annual rainfall over southern Africa are shown in Figure 1 for the far-future period 2080–2099 compared to the present-day (1971–2000). A general pattern of rainfall decreases is projected for subtropical southern Africa. An exception is Mozambique, where rainfall increases are projected for the central and northern parts in particular. There is some uncertainty in the projections over the interior of the central subcontinent, where a minority of projections indicate rainfall increases over specific regions, or decreases that are small in amplitude. The largest rainfall decreases are projected for Angola and over the southern parts of South Africa. The projected decreases in Angola may be occurring in conjunction with changes in the Angola low-pressure system and the general strengthening of the subtropical high-pressure belt over southern Africa (e.g., Engelbrecht et al., 2009). Over South Africa, the rainfall decreases projected for the southwestern Cape are occurring in association with a poleward displacement of the westerlies and frontal systems under low mitigation (e.g., Christensen et al., 2007; Engelbrecht et al., 2009).

Drastic temperature increases of 4–7°C are projected to occur over the western interior regions of southern Africa under low mitigation (Fig. 2). Relatively smaller increases are projected for Mozambique (where general increases in rainfall and cloud cover are projected) and along the coastal areas (due to the moderating effects of the ocean).

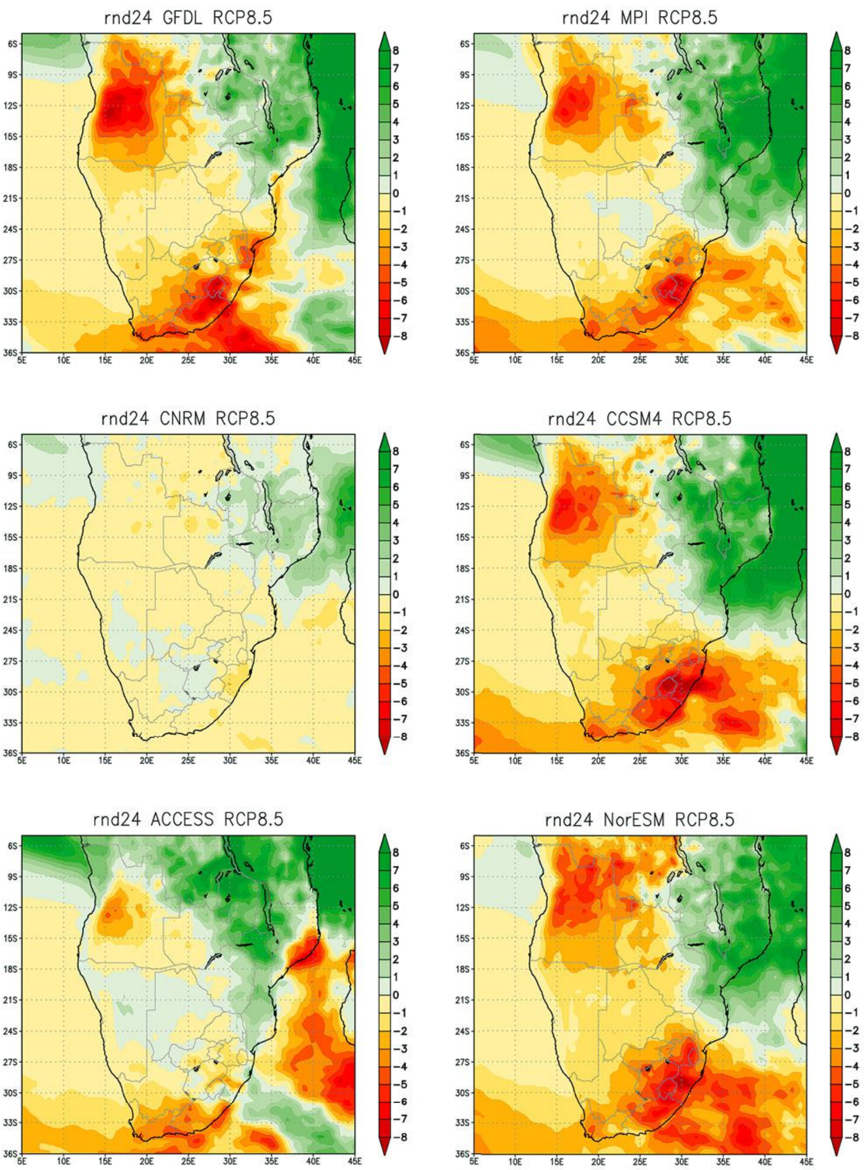

Figure 1: CCAM projected change in the annual average rainfall totals (units 10*mm/day) over southern Africa at 50 km resolution, for the time period 2080–2099 relative to 1971–2000. The downscalings were obtained from six different CMIP5 GCM projections under low mitigation (RCP8.5).

Incorporating 16 regional climate change projections conducted by GERICS (using the REMO model) and other institutions in the frame of the CORDEX initiative for the southern African region, analyses of projected changes for a set of climate indices along various transects over the SASSCAL region have been conducted based on larger regional climate model ensembles for RCP4.5 and RCP8.5. The median projection of change in annual maximum temperature is about 3°C (RCP4.5) to 5°C (RCP8.5) in the interior and about 1.5 to 2°C less at the coastal areas in the west, east, and south. The spread between the different simulations is about 2°C (RCP4.5) to 3°C (RCP8.5), leading to a maximum projected increase in maximum annual temperature of about 7°C (RCP8.5) over the semi-arid to arid western parts of the SASSCAL region (Fig. 3). The CCAM projections (Fig. 2) are consistent with the range of changes projected by the CORDEX ensemble (Fig. 3).

The SASSCAL projections and analyses convey a clear message that a low-mitigation climate future may have devastating impacts on the southern African region. Drastically rising average temperatures and related extreme events (e.g., very hot days, heat-wave days, and high fire danger) are plausible to have a negative impact on crop yield, livestock production, and human health. The general reductions in rainfall may induce further stress for rainfed agriculture in the region. For example, the Kalahari Desert receives annual precipitation rates of about 250 mm in the arid south-western parts and rising to more than 600 mm towards the centre and north-east of Botswana. For the end of the century, not only rising temperatures are projected but also a reduction in the annual rainfall rate. With a later onset of the rainy season and an earlier cessation, the number of dry days outside the rainy season increases and the rainy season itself shortens. As a result, semi-arid and arid domains are estimated to expand by 5–8%, influencing the ecosystem and its vegetation, hydrology,

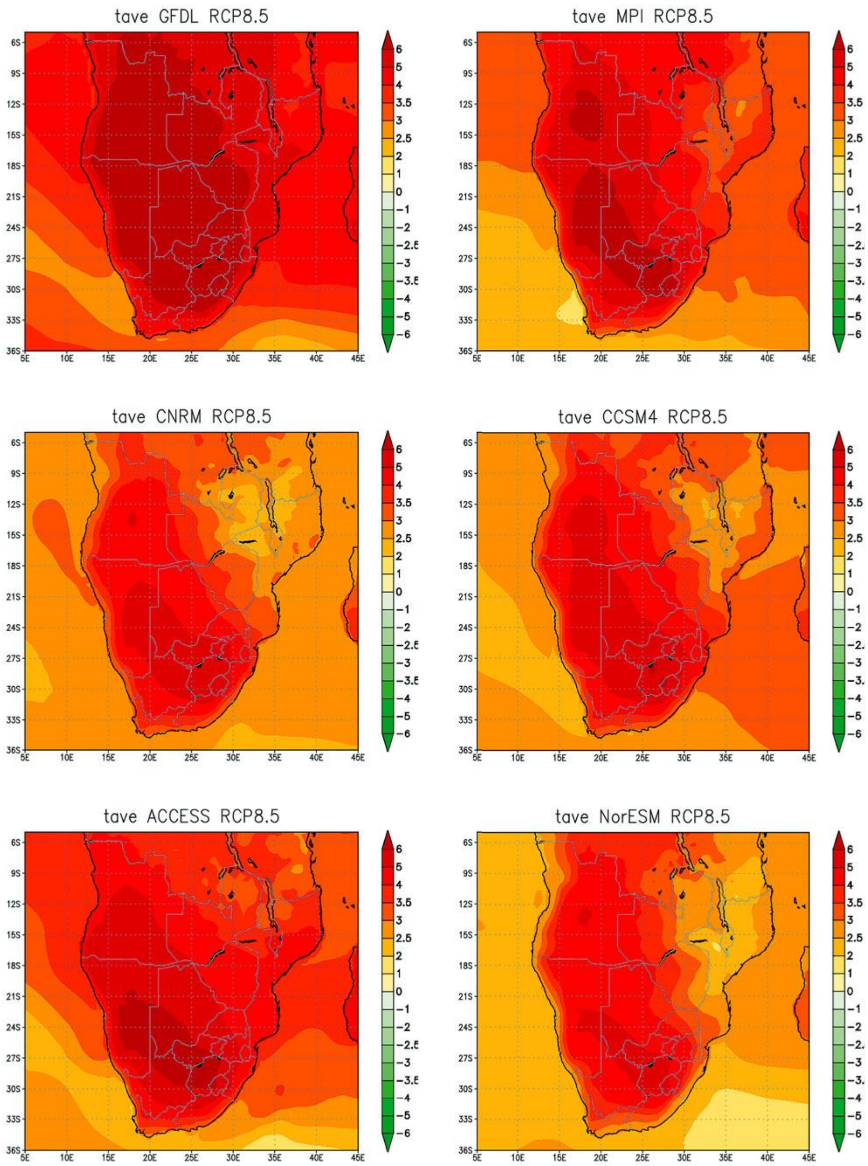

Figure 2: CCAM projected change in the annual average temperature (°C) over southern Africa at 50 km resolution, for the time period 2080–2099 relative to 1971–2000. The downscalings were obtained from six different CMIP5 GCM projections under low mitigation (RCP8.5).

and human proceedings (Stringer et al., 2009). Climate change has already been noticeably present during the past decades (Kusangaya et al., 2014), and the associated intensification and expansion of agriculture and livestock farming has reinforced land use pressure. Due to the absence of sufficient surface water resources, groundwater resources are used to address the rising demand for water and, consequently, the number of wells and boreholes in the Kalahari Desert has increased remarkably during the last century (Christelis & Struckmeier, 2011). Projected climate extremes, in combination with population growth, may cause an overutilization of limited resources in central Botswana, which in turn may cause migration to other areas.

Also, coastlines may be affected. While the west coast of southern Africa is comparably dry (< 500 mm), the east coast receives more rainfall (700–1200 mm), with a decreasing trend from north to south. As shown by Oltmanns (2015), projections indicate a decline in precipitation for most coastlines, except for northern Mozambique, for which an increase by approximately 10% is projected. A similar tendency can be seen for rainfall intensity. The west coast will barely experience extreme events (more than 20 mm/day), but an increase in extreme events is projected for the northern Mozambican coastline (declining slightly towards the south). Although aspects of agriculture in Mozambique may benefit from an increase in rainfall, the country simultaneously needs to prepare for the likelihood of an increasing number of flood events associated with landfalling tropical lows and cyclones under climate change. The plausibility of a significant reduction of rainfall over the mega-dam region of South Africa is a further cause for concern. Even under modest-high mitigation, southern Africa will experience potentially significant changes in the regional climate. Over the interior regions, temperature increases may well still reach values of 3–4°C, and it remains plausible that the region will become generally drier. Nevertheless, temperature increases under modest-high mitigation, though significant, are on the order of half the amplitude of changes under low mitigation. This implies the availability of more options for adaptation and more time to adapt before critical temperature thresholds are exceeded for the first time.

It is important to consider what the implications of the projected changes in climate may be for vegetation in southern Africa, particularly in the savannas, where complex interactions occur between grasses, trees, fire, and CO_2 (Bond & Midgley, 2012). In fact, rising levels of CO_2 strongly favour trees over grasses in the savannas, potentially causing bush encroachment and spawning the hypothesis of the "forestation of Africa" under climate change (West et al., 2012). However, the substantial reductions in rainfall projected for southern Angola and Zambia in particular, in combination with more frequent fires occurring under drastic temperature increases (Engelbrecht et al., 2015) and human-induced land degradation, may in fact result in decreasing tree cover in the savannas (Engelbrecht & Engelbrecht, 2016). Dynamic vegetation-fire models that can also incorporate scenarios of human-induced changes in land use are required to objectively project the vegetation future of southern Africa, yet few such models have to date been developed and applied over the region.

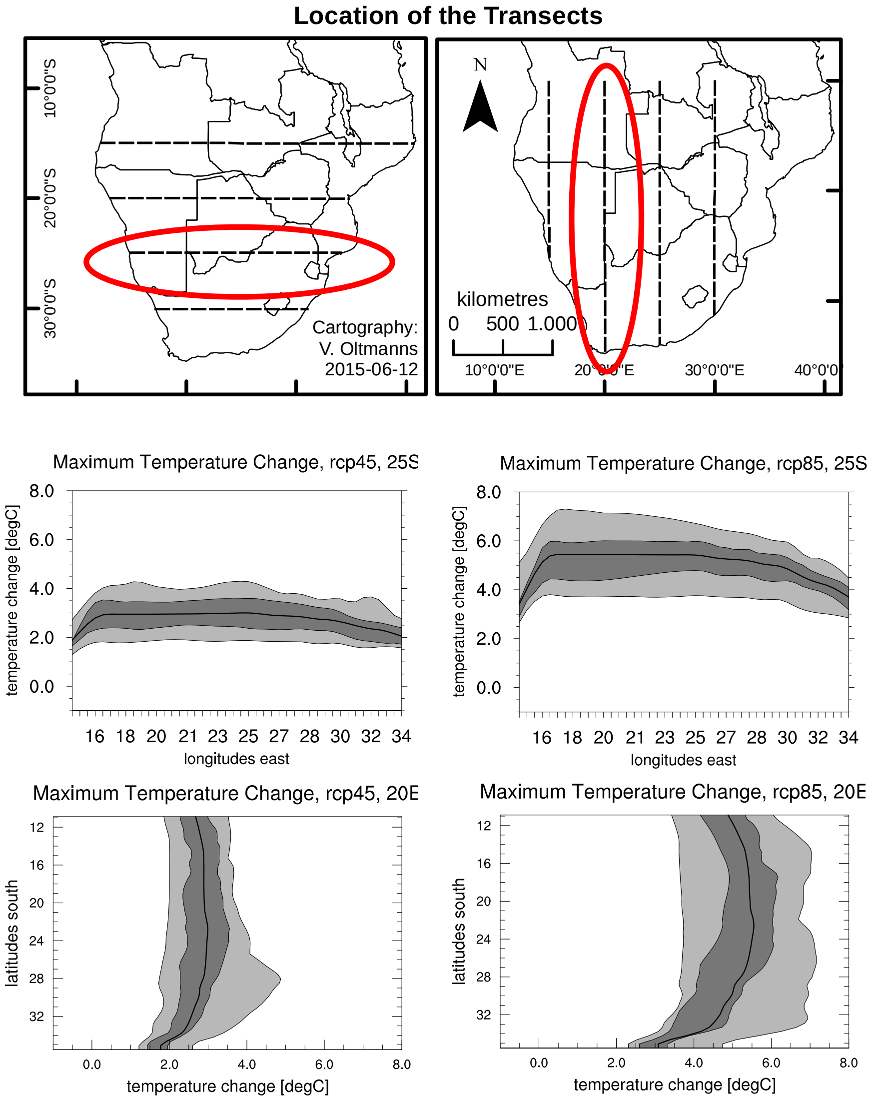

Figure 3: Range of projected changes in annual maximum temperature along an east-west (25S) and a north-south (20E) transect for the time period 2071–2100 relative to 1971–2000 for the RCP4.5 and RCP8.5 scenarios. For each of the scenarios, the projections are based on an ensemble of 16 transient regional climate change simulations from the CORDEX Africa database. The black line represents the median change. The dark-grey area reflects the range defined by the 25th to 75th percentiles of all simulations centred on the median. The light grey area spans the range between the ensemble minimum and maximum. Figures are taken from Oltmanns (2015).

Seasonal variability and early warning

Southern African seasonal climate anomalies are (generally) predictable (Barnston et al., 1996), although work in this area remains challenged by the lack of observational data in certain areas (see section to follow). The notion of a predictable climate, further supported by the discovery in the 1980s of the El Niño-Southern Oscillation (ENSO) phenomenon as a primary driver of seasonal-to-interannual variability over the region (Ropelewski & Halpert, 1987, 1989), led to the development of operational seasonal prediction systems for rainfall (Mason, 1998; Jury et al., 1999) and for temperature (Klopper et al., 1998). The initial modelling in southern Africa was undertaken mainly from the early 1990s by a number of institutions that developed statistical seasonal forecast models (Mason, 1998; Jury et al., 1999; Landman & Mason, 1999). A few years later, in the early 2000s, atmospheric general circulation models (AGCMs) for operational seasonal forecasting and research began to be used (e.g. Landman et al., 2001). Major advances in seasonal forecast system and infrastructure development have occurred since then, including the World Meteorological Organisation's recognition of the South African Weather Service (SAWS) as a Global Producing Centre for Long-Range Forecasting, the development of objective multi-model forecasting systems for southern Africa (Landman & Beraki, 2012), and, significantly, the development of a fully coupled ocean-atmosphere model at SAWS for operational seasonal forecast production (Beraki et al., 2014). Nested regional climate models as seasonal forecasting tools were also investigated (Landman et al., 2005, 2009; Kgatuke et al., 2008; Ratnam et al., 2011). A review on aspects of seasonal forecast development in South Africa can be found in Landman (2014).

After forecasts were demonstrated to obtain the highest levels of skill when statistical methods and global model forecasts are blended into a multi-tiered forecast system (Landman et al., 2001), a move away from compiling operational forecasts subjectively through consensus discussions was introduced by making use of objective multi-model forecast systems (Landman & Beraki, 2012). Over the past 10 years or so, modelling advances obtained locally were largely focused on the development, testing, and use of fully coupled ocean-atmosphere models in seasonal forecast production (Beraki et al., 2012; Landman et al., 2012), the demonstrated potential of forecasts through the development of objective applications models (Malherbe et al., 2014), and the modelling of intra-seasonal characteristics (Engelbrecht et al., 2017).

Notwithstanding these developments, a number of caveats regarding seasonal forecasting in South Africa may be identified that require the attention of modellers, forecast producers, and users of forecasts. These include (but are not limited to) the need to demonstrate the benefits derived from using seasonal forecasts, including financial benefits; expanding on the knowledge of current skill levels and identifying factors limiting forecast skill; the development and testing of forecast systems for areas of southern Africa largely neglected up to now (i.e., the south-western and southern Cape); the development of schemes

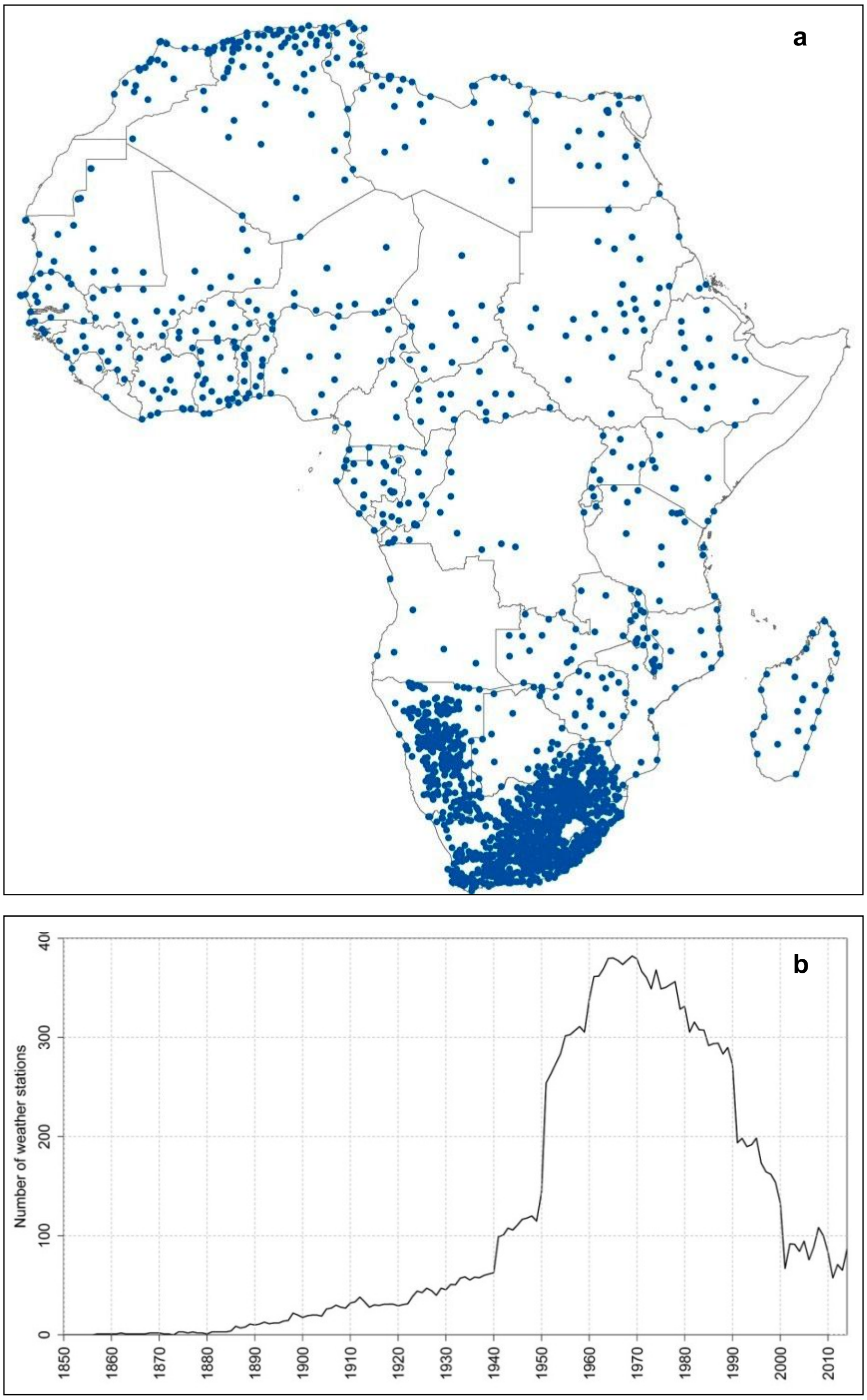

Figure 4: The locations of NOAA's Global Historical Climate Network (GHCN) weather stations, as used by CRU, across Africa (a) and the number of weather stations collecting daily temperature records across southern Africa from 1850 to 2014 used in the gridded CRUTEM4 product (b). Station density increased consistently from the start of the 20th century and peaked in the 1970s, after which it began to decline. Source: Davis & Vincent, 2017 (reproduced with the permission of the authors).

for process-based verification; the building of so-called earth system models for improved forecasts through, for example, data assimilation systems and tropical-extra-tropical ocean-land-atmosphere coupling; the operational production of forecasts to address seasonal characteristics such as onset, cessation, and sub-seasonal variations; the production and testing of high spatial and temporal resolution forecasts; operational applications model development; and, through co-production, the development of methodologies to better communicate seasonal forecast information to a variety of users in terms of complexity and application.

Data gaps and needs

Lötter et al. (2018) describe a key challenge in the SADC region as being the lack of long-term reliable climate records, particularly outside of South Africa. Such records are essential both for measurement and interpretation of current trends (e.g., Kruger & Sekele, 2013; Engelbrecht et al., 2015) and for providing the critical ability to interpret the occurrence of extreme events against the historical record. In addition, a robust observation network supports a range of tasks from shorter-term forecasting to seasonal predictions to multi-decadal climate change projections (Engelbrecht et al., 2011) through the process of model evaluation and validation and by providing options for statistical downscaling (e.g., Landman et al., 2017). It also supports adaptation efforts, such as climate index–driven insurance schemes (e.g., Malherbe et al., 2018).

Figure 4 (from Lötter et al., 2018) shows the sparseness of climate records, making it evident that certain areas are particularly poorly served. It may be noted that in this regard SASSCAL has in recent years made a considerable effort to rescue historic climate data and to expand the weather station observational network in Namibia, Botswana, Zambia, and Angola (Kaspar et al., 2015; Muche et al., 2018; Posada et al., 2018).

Moving forward

At a time of recent and current drought in both southern Africa's summer and winter rainfall periods, it is an opportune moment to consider the role of climate prediction in supporting both shorter-term coping and longer-term adaptation to climate variability and change. While improved prediction can by no means stand alone in support of improved response, improvements are essential at both a national and regional level. It is hoped that such improvements in prediction as those detailed here (including attention to gaps in data and the observational network) might be matched with improved support for response and adaptation to support the evolution of a more resilient subcontinent.

Climate

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References

Archer, E.R.M., Landman, W., Tadross, M., Malherbe, J., Weepener, H., Maluleke, P. and Marumbwa, F. (2017) Understanding the evolution of the 2014–2016 summer rainfall seasons in southern Africa: key lessons. *Climate Risk Management*, **16**, 22–28.

Barnston, A.G., Thiao, W. & Kumar, V. (1996) Long-lead forecasts of seasonal precipitation in Africa using CCA. *Weather Forecast,* **11,** 506–520.

Beraki, A.F., DeWitt, D., Landman, W.A. & Oliver, C. (2014) Dynamical seasonal climate prediction using an ocean-atmosphere coupled climate model developed in partnership between South Africa and the IRI. *J Climate*, **27,** 1719–1741.

Bond, W.J. & Midgley, G.F. (2012) Carbon dioxide and the uneasy interactions of trees and savannah grasses. *Philosophical Transactions of the Royal Society B*, **367**, 601–612.

Christelis, G. & Struckmeier, W. (2011) *Groundwater in Namibia. An explanation to the hydrogeological map*. Namibian Ministry of Agriculture, Water and Rural Development, **2**, 1–132.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W-T., Laprise, R., Magana Rueda, V., Mearns, L., Menendez, C.G., Raisanen, J., Rinke, A., Sarr, A. & Whetton, P. (2007) Regional climate projections. *Climate change 2007: the physical science basis* (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, A.B. Averyt, M. Tignor and H.L. Miller). Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Davis-Reddy, C. & Vincent, K. (2017) *Climate risk and vulnerability: a handbook for southern Africa*, 2nd ed. Council for Scientific and Industrial Research, Pretoria, South Africa.

Engelbrecht, C.J. & Engelbrecht, F.A. (2016) Shifts in Köppen-Geiger climate zones over southern Africa in relation to key global temperature goals. *Theoretical and applied climatology*, **123**, 247–261. DOI 10.1007/s00704-014-1354-1

Engelbrecht, C.J., Engelbrecht, F.A. & Dyson, L.L. (2013) High-resolution model projected changes in mid-tropospheric closed-lows and extreme rainfall events over southern Africa. *International Journal of Climatology*, **33**, 173–187. doi:10.1002/joc.3420

Engelbrecht, C.J., Landman, W.A., Graham, R.J. & McLean, P. (2017). Seasonal predictive skill of intraseasonal synoptic type variability over the Cape south coast of South Africa by making use of the Met Office Global Seasonal Forecast system 5. *International Journal of Climatology,* **37,** 1998-2012.

Engelbrecht, F.A., Landman, W.A., Engelbrecht, C.J., Landman, S., Roux, B., Bopape, M.M., McGregor, J.L. & Thatcher, M. (2011) Multi-scale climate modelling over southern Africa using a variable-resolution global model. *Water SA*, **37**, 647–658.

Engelbrecht, F.A., McGregor, J.L. & Engelbrecht, C.J. (2009) Dynamics of the conformal-cubic atmospheric model projected climate-change signal over southern Africa. *International Journal of Climatology*, **29**, 1013–1033.

Engelbrecht, F., Adegoke, J., Bopape, M.M., Naidoo, M., Garland, R., Thatcher, M., McGregor, J., Katzfey, J., Werner, M., Ichoku, C. & Gatebe, C. (2015) Projections of rapidly rising surface temperatures over Africa under low mitigation. *Environmental Research Letters*, **10**. doi: 10.1088/1748-9326/10/8/085004

Garland, R., Matooane, M., Engelbrecht, F.A., Bopape, M., Landman, W., Naidoo, M., Van der Merwe, J. & Wright, C. (2015) Regional projections of extreme apparent temperature days in Africa and the related potential risk to human health. *International Journal of Environmental Research and Public Health*, **12**, 12577–12604.

Haensler, A., Hagemann, S. & Jacob, D. (2010) How the future climate of the southern African region might look like: results of a high-resolution regional climate change projection. *Nova Acta Leopoldina*, **112**, 183–193.

Haensler, A., Hagemann, S., & Jacob, D. (2011) The role of the simulation setup in a long-term high-resolution climate change projection for the southern African region. *Theoretical and Applied Climatology*, **106,** 153-169.

James, R. & Washington, R. (2013) Changes in African temperature and precipitation associated with degrees of global warming. *Climatic Change*, **117**, 859–872. doi:10.1007/s10584-012-0581-7

Jury, M.R., Mulenga, H.M. & Mason, S.J. (1999) Exploratory longrange models to estimate summer climate variability over southern Africa. *Journal of Climate,* **12,** 1892–1899.

Kaspar, F., Helmschrot, J., Mhanda, A. et al. (2015) The SASSCAL contribution to climate observation, climate data management and data rescue in Southern Africa. *Advances in Science and Research*, **12**, 171–177.

Kgatuke, M.M., Landman, W.A., Beraki, A. & Mbedzi, M. (2008) The internal variability of the RegCM3 over South Africa. *International Journal of Climatology,* **28,** 505–520.

Klopper, E., Landman, W.A. and Van Heerden, J. (1998) The predictability of seasonal maximum temperature in South Africa. *International Journal of Climatology,* **18,** 741–758.

Kruger, A.C. & Sekele, S.S. (2013) Trends in extreme temperature indices in South Africa: 1962–2009. *International Journal of Climatology*, **33**, 661–676.

Kusangaya, S., Warburton, M., Archer van Garderen, E. & Jewitt, G. (2014) Impacts of climate change on water resources in southern Africa: a review. *Physics and Chemistry of the Earth*, **67**, 47–54.

Landman, W.A. (2014) How the International Research Institute for Climate and Society has contributed towards seasonal climate forecast modelling and operations in South Africa. *Earth Perspectives,* **1,** 22.

Landman, W.A. & Beraki, A. (2012) Multi-model forecast skill for mid-summer rainfall over southern Africa. *International Journal of Climatology,* **32,** 303–314.

Landman, W.A., DeWitt, D. Lee, D.-E., Beraki, A. & Lötter, D. (2012). Seasonal rainfall prediction skill over South Africa: 1- vs. 2-tiered forecasting systems. *Weather and Forecasting,* **27,** 489-501.

Landman, W.A., Engelbrecht, F.A., Hewitson, B., Malherbe, J., & Van der Merwe, J. (2017) Towards bridging the gap between climate change projections and maize producers in South Africa. *Theoretical and Applied Climatology*, 11-17.

Landman, W.A., Kgatuke, M.M., Mbedzi, M., Beraki, A., Bartman, A. & du Piesanie, A. (2009) Performance comparison of some dynamical and empirical downscaling methods for South Africa from a seasonal climate modelling perspective. *International Journal of Climatology* **29**, 1535-1549.

Landman, W.A. & Mason, S.J. (1999) Operational long-lead prediction of South African rainfall using canonical correlation analysis. *International Journal of Climatology,* **19,** 1073–1090.

Landman, W.A., Mason, S.J., Tyson, P.D. & Tennant, W.J. (2001) Retro-active skill of multitiered forecasts of summer rainfall over southern Africa. *International Journal of Climatology,* **21,** 1–19.

Landman, W.A., Seth, A., Camargo, S.J. (2005) The effect of regional climate model domain choice on the simulation of tropical cyclone-like vortices in the southwestern Indian Ocean. *Journal of Climate*, **18,** 1263–1274.

Lötter, D., Davis, C., Archer, E., Vincent, L., Pardoe, J., Tadross, M., Landman. W., Stuart-Hill, S. & Tadross, M. (2018) *Climate information needs in southern Africa*. CCCEP Working Paper (under review).

Malherbe, J., Engelbrecht, F.A. & Landman, W.A. (2013) Projected changes in tropical cyclone climatology and landfall in the Southwest Indian Ocean region under enhanced anthropogenic forcing. *Climate Dynamics*, **40**, 2867–2886.

Malherbe, J., Iyahen, E., Engelbrecht, F., Chamunorwa, M. & Helmschrot, J. (2018) The Extreme Climate Index (ECI), a tool for monitoring regional extreme events. This volume.

Malherbe, J., Landman, W.A., Olivier, C., Sakuma, H. & Luo, J.-J. (2014). Seasonal forecasts of the SINTEX-F coupled model applied to maize yield and streamflow estimates over north-eastern South Africa. *Meteorological Applications,* **21,** 733-742.

Mason, S.J. (1998) Seasonal forecasting of South African rainfall using a non-linear discriminant analysis model. *International Journal of Climatology,* **18,** 147–164.

McGregor, J.L. (2005) C-CAM geometric aspects and dynamical formulation. CSIRO Atmospheric Research Technical Paper, 70.

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: present state, challenges, and achievements of the regional climatic observation network and database. This volume.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J. & Urquhart, P. (2014) Africa. *Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects* (ed. by V.R. Barros, C.B. Field, D.J. Dokken et al.), pp. 1199–1265. Cambridge University Press, Cambridge, UK.

Oltmanns, V. (2015). *Analysing regional rainfall and temperature dynamics in Southern Africa using CORDEX climate projections*. MSc thesis, Friedrich Schiller University Jena (unpublished).

Posada R., Riede, J., Kaspar, F., Mhanda, A., Radithupa, M., Stegling, J., Nascimento, D., Tima, L., Kanyanga, J., Nkonde, E., Swaswa, M. & Waitolo, D. (2018) Cooperation of meteorological services within SASSCAL on improving the management of observed climate data. This volume.

Ratnam, J.V., Behera, S.K., Masumoto, Y., Takahashi, K. & Yamagata, T. (2011) A simple regional coupled model experiment for summertime climate simulation over southern Africa. *Climate Dynamics*, **39,** 2207–2217.

Ropelewski, C.F. & Halpert, M.S. (1987) Global and regional scale precipitation patterns associated with the El Niño–Southern Oscillation. *Monthly weather review,* **115,** 1606–1626.

Ropelewski, C.F. & Halpert, M.S. (1989) Precipitation patterns associated with the high index of the Southern Oscillation. *Journal of Climate,* **2**, 268–284.

Stringer, L., Dyer, J., Reed, M., Dougill, A., Twyman, C. & Mkwambisi, D. (2009) Adaptations to climate change, drought and desertification: local insights to enhance policy in southern Africa. *Environmental Science and Policy*, **12**, 748–765.

West, A.G., Midgley, G.F. & Bond, W.J. (2012) The reforestation of Africa? *South African Journal of Science*, **108**, 2–4.

Winsemius, H.C., Dutra, E., Engelbrecht, F.A., Archer Van Garderen, E., Wetterhall, F., Pappenberger, F. & Werner, M.G.F. (2014) The potential value of seasonal forecasts in a changing climate in southern Africa. *Hydrology and Earth System Sciences*, **18**, 1525–1538.

References [CrossRef]

Archer, E.R.M., Landman, W., Tadross, M., Malherbe, J., Weepener, H., Maluleke, P. and Marumbwa, F. (2017) Understanding the evolution of the 2014–2016 summer rainfall seasons in southern Africa: key lessons. *Climate Risk Management*, **16**, 22–28. CrossRef

Barnston, A.G., Thiao, W. & Kumar, V. (1996) Long-lead forecasts of seasonal precipitation in Africa using CCA. *Weather Forecast*, **11,** 506–520. CrossRef

Beraki, A.F., DeWitt, D., Landman, W.A. & Oliver, C. (2014) Dynamical seasonal climate prediction using an ocean-atmosphere coupled climate model developed in partnership between South Africa and the IRI. *J Climate*, **27,** 1719–1741. CrossRef

Bond, W.J. & Midgley, G.F. (2012) Carbon dioxide and the uneasy interactions of trees and savannah grasses. *Philosophical Transactions of the Royal Society B*, **367**, 601–612. CrossRef

Christelis, G. & Struckmeier, W. (2011) *Groundwater in Namibia. An explanation to the hydrogeological map*. Namibian Ministry of Agriculture, Water and Rural Development, **2**, 1–132.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W-T., Laprise, R., Magana Rueda, V., Mearns, L., Menendez, C.G., Raisanen, J., Rinke, A., Sarr, A. & Whetton, P. (2007) Regional climate projections. *Climate change 2007: the physical science basis* (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, A.B. Averyt, M. Tignor and H.L. Miller). Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Davis-Reddy, C. & Vincent, K. (2017) *Climate risk and vulnerability: a handbook for southern Africa*, 2nd ed. Council for Scientific and Industrial Research, Pretoria, South Africa.

Engelbrecht, C.J. & Engelbrecht, F.A. (2016) Shifts in Köppen-Geiger climate zones over southern Africa in relation to key global temperature goals. *Theoretical and applied climatology*, **123**, 247–261. CrossRef

Engelbrecht, C.J., Engelbrecht, F.A. & Dyson, L.L. (2013) High-resolution model projected changes in mid-tropospheric closed-lows and extreme rainfall events over southern Africa. *International Journal of Climatology*, **33**, 173–187. CrossRef

Engelbrecht, C.J., Landman, W.A., Graham, R.J. & McLean, P. (2017). Seasonal predictive skill of intraseasonal synoptic type variability over the Cape south coast of South Africa by making use of the Met Office Global Seasonal Forecast system 5. *International Journal of Climatology*, **37,** 1998-2012. CrossRef

Engelbrecht, F.A., Landman, W.A., Engelbrecht, C.J., Landman, S., Roux, B., Bopape, M.M., McGregor, J.L. & Thatcher, M. (2011) Multi-scale climate modelling over southern Africa using a variable-resolution global model. *Water SA*, **37**, 647–658. CrossRef

Engelbrecht, F.A., McGregor, J.L. & Engelbrecht, C.J. (2009) Dynamics of the conformal-cubic atmospheric model projected climate-change signal over southern Africa. *International Journal of Climatology*, **29**, 1013–1033. CrossRef

Engelbrecht, F., Adegoke, J., Bopape, M.M., Naidoo, M., Garland, R., Thatcher, M., McGregor, J., Katzfey, J., Werner, M., Ichoku, C. & Gatebe, C. (2015) Projections of rapidly rising surface temperatures over Africa under low mitigation. *Environmental Research Letters*, **10**. CrossRef

Garland, R., Matooane, M., Engelbrecht, F.A., Bopape, M., Landman, W., Naidoo, M., Van der Merwe, J. & Wright, C. (2015) Regional projections of extreme apparent temperature days in Africa and the related potential risk to human health. *International Journal of Environmental Research and Public Health*, **12**, 12577–12604. CrossRef

Haensler, A., Hagemann, S. & Jacob, D. (2010) How the future climate of the southern African region might look like: results of a high-resolution regional climate change projection. *Nova Acta Leopoldina*, **112**, 183–193.

Haensler, A., Hagemann, S., & Jacob, D. (2011) The role of the simulation setup in a long-term high-resolution climate change projection for the southern African region. *Theoretical and Applied Climatology*, **106,** 153-169. CrossRef

James, R. & Washington, R. (2013) Changes in African temperature and precipitation associated with degrees of global warming. *Climatic Change*, **117**, 859–872. CrossRef

Jury, M.R., Mulenga, H.M. & Mason, S.J. (1999) Exploratory longrange models to estimate summer climate variability over southern Africa. *Journal of Climate*, **12,** 1892–1899. CrossRef

Kaspar, F., Helmschrot, J., Mhanda, A. et al. (2015) The SASSCAL contribution to climate observation, climate data management and data rescue in Southern Africa. *Advances in Science and Research*, **12**, 171–177. CrossRef

Kgatuke, M.M., Landman, W.A., Beraki, A. & Mbedzi, M. (2008) The internal variability of the RegCM3 over South Africa. *International Journal of Climatology*, **28,** 505–520. CrossRef

Klopper, E., Landman, W.A. and Van Heerden, J. (1998) The predictability of seasonal maximum temperature in South Africa. *International Journal of Climatology*, **18,** 741–758. CrossRef

Kruger, A.C. & Sekele, S.S. (2013) Trends in extreme temperature indices in South Africa: 1962–2009. *International Journal of Climatology*, **33**, 661–676. CrossRef

Kusangaya, S., Warburton, M., Archer van Garderen, E. & Jewitt, G. (2014) Impacts of climate change on water resources in southern Africa: a review. *Physics and Chemistry of the Earth*, **67**, 47–54. CrossRef

Landman, W.A. (2014) How the International Research Institute for Climate and Society has contributed towards seasonal climate forecast modelling and operations in South Africa. *Earth Perspectives*, **1,** 22. CrossRef

Landman, W.A. & Beraki, A. (2012) Multi-model forecast skill for mid-summer rainfall over southern Africa. *International Journal of Climatology*, **32,** 303–314. CrossRef

Landman, W.A., DeWitt, D. Lee, D.-E., Beraki, A. & Lötter, D. (2012). Seasonal rainfall prediction skill over South Africa: 1- vs. 2-tiered forecasting systems. *Weather and Forecasting*, **27,** 489-501. CrossRef

Landman, W.A., Engelbrecht, F.A., Hewitson, B., Malherbe, J., & Van der Merwe, J. (2017) Towards bridging the gap between climate change projections and maize producers in South Africa. *Theoretical and Applied Climatology*, 11-17. CrossRef

Landman, W.A., Kgatuke, M.M., Mbedzi, M., Beraki, A., Bartman, A. & du Piesanie, A. (2009) Performance comparison of some dynamical and empirical downscaling methods for South Africa from a seasonal climate modelling perspective. *International Journal of Climatology* **29**, 1535-1549. CrossRef

Landman, W.A. & Mason, S.J. (1999) Operational long-lead prediction of South African rainfall using canonical correlation analysis. *International Journal of Climatology*, **19,** 1073–1090. CrossRef

Landman, W.A., Mason, S.J., Tyson, P.D. & Tennant, W.J. (2001) Retro-active skill of multitiered forecasts of summer rainfall over southern Africa. *International Journal of Climatology*, **21,** 1–19. CrossRef

Landman, W.A., Seth, A., Camargo, S.J. (2005) The effect of regional climate model domain choice on the simulation of tropical cyclone-like vortices in the southwestern Indian Ocean. *Journal of Climate*, **18,** 1263–1274. CrossRef

Lötter, D., Davis, C., Archer, E., Vincent, L., Pardoe, J., Tadross, M., Landman. W., Stuart-Hill, S. & Tadross, M. (2018) *Climate information needs in southern Africa*. CCCEP Working Paper (under review).

Malherbe, J., Engelbrecht, F.A. & Landman, W.A. (2013) Projected changes in tropical cyclone climatology and landfall in the Southwest Indian Ocean region under enhanced anthropogenic forcing. *Climate Dynamics*, **40**, 2867–2886. CrossRef

Malherbe, J., Iyahen, E., Engelbrecht, F., Chamunorwa, M. & Helmschrot, J. (2018) The Extreme Climate Index (ECI), a tool for

monitoring regional extreme events. This volume. CrossRef
Malherbe, J., Landman, W.A., Olivier, C., Sakuma, H. & Luo, J.-J. (2014). Seasonal forecasts of the SINTEX-F coupled model applied to maize yield and streamflow estimates over north-eastern South Africa. *Meteorological Applications*, **21,** 733-742. CrossRef
Mason, S.J. (1998) Seasonal forecasting of South African rainfall using a non-linear discriminant analysis model. *International Journal of Climatology*, **18,** 147–164. CrossRef
McGregor, J.L. (2005) C-CAM geometric aspects and dynamical formulation. CSIRO Atmospheric Research Technical Paper, 70.
Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: present state, challenges and achievements of the regional climatic observation network and database. This volume. CrossRef
Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J. & Urquhart, P. (2014) Africa. *Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects* (ed. by V.R. Barros, C.B. Field, D.J. Dokken et al.), pp. 1199–1265. Cambridge University Press, Cambridge, UK.
Oltmanns, V. (2015). *Analysing regional rainfall and temperature dynamics in Southern Africa using CORDEX climate projections*. MSc thesis, Friedrich Schiller University Jena (unpublished).
Posada R., Riede, J., Kaspar, F., Mhanda, A., Radithupa, M., Stegling, J., Nascimento, D., Tima, L., Kanyanga, J., Nkonde, E., Swaswa, M. & Waitolo, D. (2018) Cooperation of meteorological services within SASSCAL on improving the management of observed climate data. This volume. CrossRef
Ratnam, J.V., Behera, S.K., Masumoto, Y., Takahashi, K. & Yamagata, T. (2011) A simple regional coupled model experiment for summer-time climate simulation over southern Africa. *Climate Dynamics*, **39,** 2207–2217. CrossRef
Ropelewski, C.F. & Halpert, M.S. (1987) Global and regional scale precipitation patterns associated with the El Niño–Southern Oscillation. *Monthly weather review,* **115,** 1606–1626. CrossRef
Ropelewski, C.F. & Halpert, M.S. (1989) Precipitation patterns associated with the high index of the Southern Oscillation. *Journal of Climate,* **2**, 268–284. CrossRef
Stringer, L., Dyer, J., Reed, M., Dougill, A., Twyman, C. & Mkwambisi, D. (2009) Adaptations to climate change, drought and desertification: local insights to enhance policy in southern Africa. *Environmental Science and Policy*, **12**, 748–765. CrossRef
West, A.G., Midgley, G.F. & Bond, W.J. (2012) The reforestation of Africa? *South African Journal of Science*, **108**, 2–4. CrossRef
Winsemius, H.C., Dutra, E., Engelbrecht, F.A., Archer Van Garderen, E., Wetterhall, F., Pappenberger, F. & Werner, M.G.F. (2014) The potential value of seasonal forecasts in a changing climate in southern Africa. *Hydrology and Earth System Sciences*, **18**, 1525–1538. CrossRef

Climate

Cooperation of meteorological services within SASSCAL on improving the management of observed climate data

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Abstract: Consistent and reliable climate observations for Southern Africa are an important source of information for climate service-related activities. Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) supported the cooperation among the national meteorological services of Angola, Botswana, Germany, and Zambia to improve the management of observed climate data in the region. This cooperation allowed the stablisation of a climate data management system in which CLIMSOFT – a freely available software suite for storing climate data – is the main component. Additional open-source applications have been developed to provide an easy-to-use interface to visualize, download, digitize, and import climate data from and into CLIMSOFT. Besides that, substantial progress in the storage, quality control, and management of present and historical climate data recorded in paper media has been achieved. The measures taken were accompanied by continuous training and support to ensure the long-term maintenance of the new data management.

Resumo: Observações climáticas consistentes e fiáveis da África Austral são uma fonte importante de informação para actividades relacionadas com serviços climáticos. O SASSCAL ("Southern African Science Service Centre for Climate Change and Adaptive Land Management" ou Centro de Serviços Científicos da África Austral para as Alterações Climáticas e a Gestão Adaptativa das Terras) apoiou a cooperação entre os serviços meteorológicos nacionais de Angola, Botswana, Alemanha e Zâmbia, de modo a melhorar a gestão dos dados climáticos observados na região. Esta cooperação permitiu o estabelecimento de um sistema de gestão de dados climáticos, em que o CLIMSOFT – um software disponível gratuitamente para o armazenamento de dados climáticos – age como o principal componente. Outros aplicativos de código aberto foram desenvolvidos, de modo a oferecer uma interface fácil de usar para visualizar, descarregar, digitalizar e importar dados climáticos, de e para o CLIMSOFT. Para além disso, foram realizados progressos substanciais no armazenamento, controlo de qualidade e gestão de dados climáticos actuais e históricos registados em papel. As medidas tomadas foram acompanhadas por formação e apoio contínuos, de modo a garantir a manutenção a longo prazo da nova gestão de dados.

Introduction

Climate data are needed to support climate research, climate adaptation measures and climate services to mitigate the effects of severe weather conditions, such as the drought associated with El Niño in 2016 that affected parts of the Southern African region (UNOCHA, 2016). Under such conditions, historical climate observations provide an important source of information for decision-makers to estimate the regional effects of climate variability and change. In comparison with other regions, however, the availability of high-quality, high-density climate observations is still low in some parts of Southern Africa. Here, we use the term "climate data" for meteorological observations taken by regular surface weather stations either by manual observers or automatic sensors. Typical parameters observed at such stations are air temperature, precipitation, pressure, humidity, wind, solar irradiance, etc. They are most useful for climate assessments if these stations are operated over a sufficiently long period of time (i.e., preferably decades). Metadata provide supplementary information on the stations, such as on the technical configuration or observation procedures (see, e.g., WMO, 2014).

In addition, the accessibility of long historical climate records for several Southern African countries is limited in that they have been recorded on paper and are not yet available in digital form (Kaspar et al., 2015a).

Concerning the present-day ground-based climate observations, SASSCAL has supported the installation of automatic weather stations (AWSs) in the region to address the lack of such observations. Currently, the SASSCAL's AWS network comprises 145 stations, and their data are freely available on the website of the SASSCAL-WeatherNet (see http://www.sasscalweathernet.org/). For more information about the SASSCAL-WeatherNet, please refer to the (Muche et al., 2018).

Currently, only a few weather stations in the region are transferring data to international data centres (Fig. 1). The exchange of such data is essential to improving the reliability and accuracy of regional and global climate analysis, climate data products, and various types of models of the components of the Earth's climate system.

The need to improve the capacities of national meteorological services (NMSs) in some regions is widely acknowledged. In this context, the World Meteorological Organization (WMO) initiated the Global Framework for Climate Services, a coordination framework of which capacity building is one of the key components. Cooperation is essential for the success of this global framework, especially between national and regional meteorological services. The collaboration between NMSs presented here and focused on improving local skills to provide better advice for decision-makers and stakeholders is an example of such a cooperative activity.

In this context, the NMSs of Angola, Botswana, and Zambia have been working closely together with Germany's national meteorological service, Deutscher Wetterdienst (DWD), to improve the management of climate data. The long experience of DWD on climate observation, climate data service provision, and data rescue (Kaspar et al., 2013; Kaspar et al., 2015b) makes it a valid partner to provide expertise and support to the meteorological services in the region. The cooperation focused specifically on (1) the implementation of a climate data management system (CDMS), (2) data rescue activities, and (3) capacity building on climate data management.

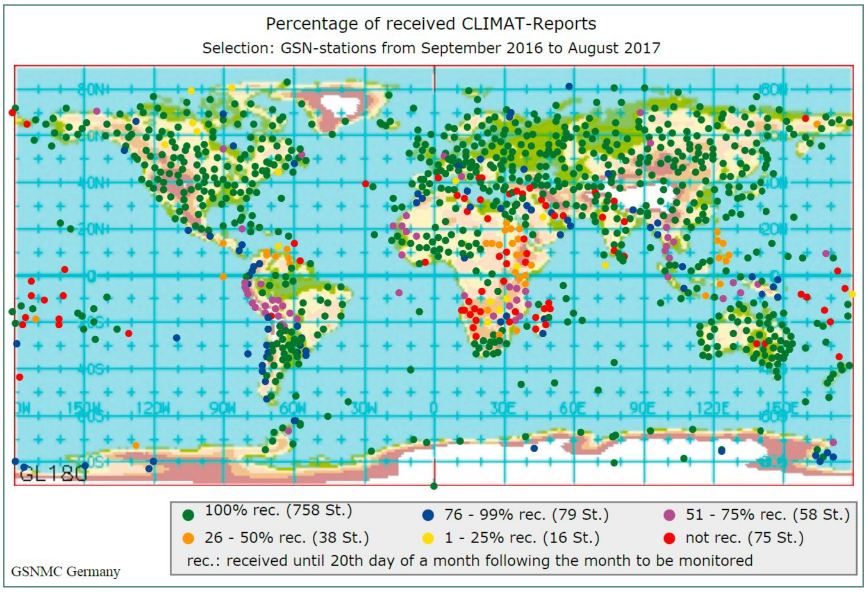

Figure 1: Percentage of received monthly CLIMAT-reports from the Global Climate Observing: System Surface Network stations (GSN) for the period of September 2016 to August 2017. Colours indicate the percentage of reports that were received by the GSN Monitoring Centre of DWD up to the 20th day of the month following the month observed.

The methods used to achieve these goals and the main results of the cooperation are presented in the following sections.

Methods

Implementation of a climate data management system

The cooperation aimed to implement a reliable CDMS, which is defined by WMO as "an integrated computer-based system that facilitates the effective archival, management, analysis, delivery and utilization of a wide range of integrated climate data" (WMO, 2014). The delegates of the NMSs of Angola, Botswana, Zambia, and Germany discussed the different existing CDMSs during a SASSCAL workshop held in Namibia in April 2014. It was agreed that CLIMSOFT ("CLIMatic SOFTware") would be the preferred option, since all countries had already used this software occasionally (Hänsler, 2014).

CLIMSOFT was developed by an African team to provide a free and easy-to-use CDMS (Stuber et al., 2011). It has an intuitive graphical user interface with a key-entry module, quality control procedures, and data import options that allow the importation of data from various sources, including data from automatic weather stations (Kaspar et al., 2015a). The import option for the data recorded by the AWSs, called "AWS-Real time", is able to read the ASCII files generated by the AWS once a user specifies the structure of the data saved in the files. The transfer is typically carried out every 10 minutes and imports the data from the last 2 hours. However, these time steps can be adjusted by the user.

The newest version of CLIMSOFT (version 4.0) is supported by a large community of developers and is based on WMO's climate data management system specifications (WMO, 2014), so that most of the components that are required for a CDMS will be featured in the software. More information about CLIMSOFT and its future releases can be found at http://www.climsoft.org. It should be noted that although CLIMSOFT provides a reliable option for storage of climate data, it was necessary to improve the accessibility of these data for subsequent analysis. In this context, we developed an open-source tool for the visualization, analysis, and download of data stored in any CLIMSOFT database. This tool, called

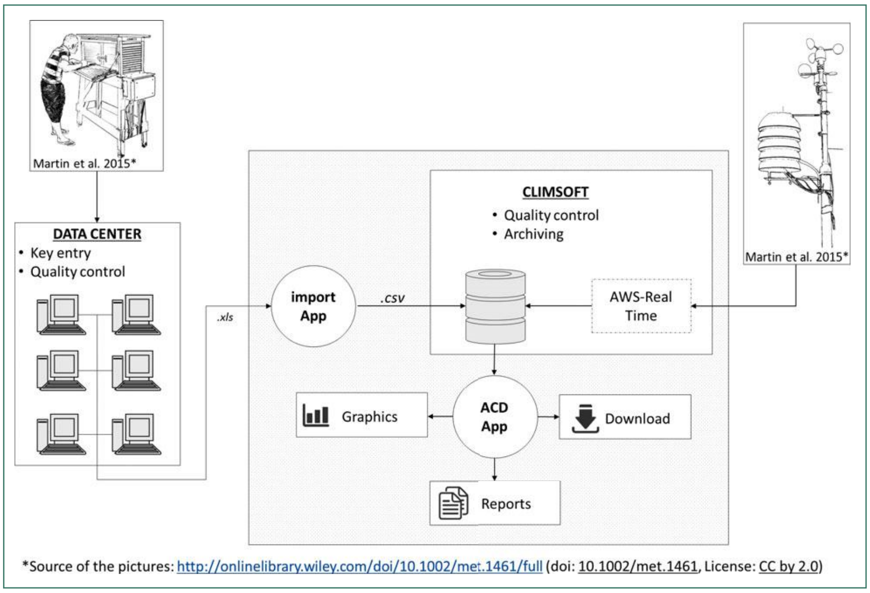

Figure 2: Data flow at INAMET. The CLIMSOFT database is the core of the CDMS, as it stores the data coming from the manual weather stations (left side) and AWSs (right side). The ACD-App allows users to create different types of products using the data stored in the database.

Analysis of Climate Data (hereafter ACD-App) is described in more detail in Posada & Riede (2018a).

Data rescue

As defined by Tan et al. (2004), data rescue is “the ongoing process of (1) preserving all data at risk of being lost due to deterioration of the medium and; (2) digitizing current and past data into computer compatible form for easy access”. This is an important aspect of the cooperation, especially at the meteorological services of Botswana and Zambia, where digitization of on-paper data is of high priority.

To facilitate the digitization, the SASSCAL team has developed an open-source tool in which users can enter the data into a table with the same structure as the on-paper form. This tool, called keyEntry App, is described in detail in Posada & Riede (2018b). The data entered with this tool can also easily be imported by CLIMSOFT using a recently developed tool called import-App, which is described in Posada & Riede (2018c).

Capacity building on climate data management

Visits of DWD staff to the NMSs were performed periodically and were intended as an opportunity to transfer knowledge to the NMS staff in the fields of metadata, importance of data management, application of a CDMS, quality control, and many further issues related to the management of observed climate data. In addition, trainings in programming languages and international data transfer standards have been carried out.

Results

The cooperation of the NMSs of Angola, Botswana, and Zambia with DWD started in 2014 with the evaluation of the facilities and resources concerning climate data management in each NMS. These led to identifying the actual needs of each country, which differ from one to the other. This section summarizes the main results achieved in each meteorological service.

Instituto Nacional de Meteorología e Geofísica, INAMET, Angola

Implementation of a CDMS

The cooperation between DWD and INAMET started in April 2014. At that time, the NMS was not operating any CDMS. The climate data from manual weather stations were entered manually into electronic spreadsheets without a standard template. These spreadsheets were saved in unnetworked PCs and in different folders, making it difficult to know which data were already available in digital form. In addition, the data recorded by AWSs were automatically transferred from the stations to a server located at INAMET in ASCII formats.

As a first step to improve this situation, a new data-flow scheme was designed so that the climate data could be collected in a proper CDMS (see Fig. 2). As stated in Section 2, the preferred CDMS was CLIMSOFT, since it had been used once at INAMET back in 2007. INAMET started by giving a unique local identifier to each manual weather station and creating an internal network to connect all the PCs used for data entry. Spreadsheet templates have been designed to facilitate the data entry process and to avoid inconsistencies between the different files. The data entered in the new format can be easily imported into CLIMSOFT by using an application programmed with R for this purpose. It is expected that in the near future, the keyEntry-App will replace the spreadsheets for entering data from manual weather stations.

Regarding the data recorded by INAMET’s AWS network (including the stations from the SASSCAL-WeatherNet), it was possible to set up CLIMSOFT’s “AWS-Real time” feature to automatically transfer these data into the database.

Finally, the ACD-App developed in the framework of SASSCAL has been installed and is currently used for quality control and downloading the data.

Data rescue

According to WMO (2016), the first task of data rescue is to locate the data. As part of this search process, WMO recommends cross-checking available digital records to determine whether historical observation records have already been digitized, identify significant gaps, and complement the data already organized, digitized, and managed within the NMS. This is of special interest in countries with a colonial history, since their records are often hosted elsewhere. Following this recommendation, INAMET decided to collect historical observation datasets from Angola that have already been digitized and that are available at international archives. To date, a total of seven different datasets have been identified that contain data from Angola (see Tab. 1). Some of these data were already digitized in INAMET, but a thorough cross-check of these data against those stored in INAMET's main database is still required to fill in the gaps. Therefore, the historical data from the international archives are being kept in a separate CLIMSOFT database until this cross-check has been carried out and completed.

Furthermore, efforts have concentrated on rescuing historical data entered on paper forms. As a first step, INAMET's archive has been reorganized so that the digitization of the data can start at any time. The keyEntry-App could be used to facilitate the key-entry of the historical data.

Capacity building

As capacity building is one of SASSCAL's main objectives, the cooperation between DWD and INAMET also focused on strengthening capacities in climate data management, especially among those staff responsible for maintaining the CDMS. The first training activities focused on basic concepts related to climate data such as the relevance of metadata and their importance to identifying inhomogeneities in a given dataset. In addition, the meteorological staff was also trained in CLIMSOFT and in an open-source computing language to facilitate future statistical analysis of the data. The main training activities made at INAMET are listed in Table 2. Furthermore, continuous supervision was provided by DWD not only through several working visits but also remotely from Germany. The aim of these activities was to ensure the proper functioning of the CDMS and the open-source apps and to improve the staff's technical capacity so that the system could run sustainably once the SASSCAL initiative had finished. A photo of a training event at INAMET is shown in Fig. 3. Further information regarding the cooperation between DWD and INAMET is given by Posada et al. (2016).

Table 1: Overview of Angolan data availability in international datasets. An extended overview – which includes further information such as the element variables available in each dataset – is given by Posada et al. (2016)

Dataset: Name	Dataset: Description	Time resolution	Source
DWD (WMO Reports)	Deutscher Wetterdienst	DAILY	DWD Database (data not available online)
		MONTHLY	DWD Database (data not available online)
GPCC	Global Precipitation Climate Centre	MONTHLY	Data requested by INAMET
GHCN	Global Historical Climatology Network	DAILY	http://doi.org/10.7289/V5D21VHZ (Menne et al., 2012a,b)
		MONTHLY	http://www.ncdc.noaa.gov/ghcnm/v3.php (Lawrimore et al., 2011) http://www.ncdc.noaa.gov/ghcnm/v2.php (Peterson & Vose, 1997)
RBIS	River Basin Information System	DAILY	http://leutra.geogr.uni-jena.de/sasscalRBIS/metadata/start.php
ISTI	International Surface Temperature Initiative	MONTHLY	ftp://ftp.ncdc.noaa.gov/pub/data/globaldatabank/monthly/stage2/colonialera/ (Thorne et al., 2011)
CDIAC	Carbon Dioxide Information Analysis Center	HOURLY	ftp://cdiac.esd.ornl.gov/pub/ndp026c/ (Hahn & Warren, 2009)
IDL	Instituto Dom Luis	HOURLY	Data provided through personal communication (data not available online)
		DAILY	Data provided through personal communication (data not available online)

Table 2: List of training events carried out in each country

NMS (Country)	Training	Dates
INAMET (Angola)	Training on keyEntry-App, import-App, and ACD-App	11–15 September 2017
	Climate data management	18–20 March 2015
	CLIMSOFT and R software	24–25 March 2015
	CLIMSOFT installation and data entry	8–13 August 2014
DMS (Botswana)	Training on keyEntry-App and import-App	4–6 October 2017
	Data rescue management (II)	3–10 March 2016
	Climate data management	23–26 February 2015
	Data rescue management	16–19 November 2015
	Data management and R tool installation guidance for technicians	17–18 November 2015; 29 February–4 March 2016
ZMD (Zambia)	Training on keyEntry-App, import-App, and ACD-App	18–22 September 2017
	R for climate products	22 January 2016
	Importance of archiving on-paper documents	19–29 April 2016
	Climate data management	23 June–1 July 2015
	Climate data management systems: CLIMSOFT	12–18 November 2014

Figure 3: Training activity at INAMET on 11 August 2014. The local technician Mr. Dario Pimentel provides support to the INAMET Data Centre team on how to enter on-paper data into the new electronic forms.

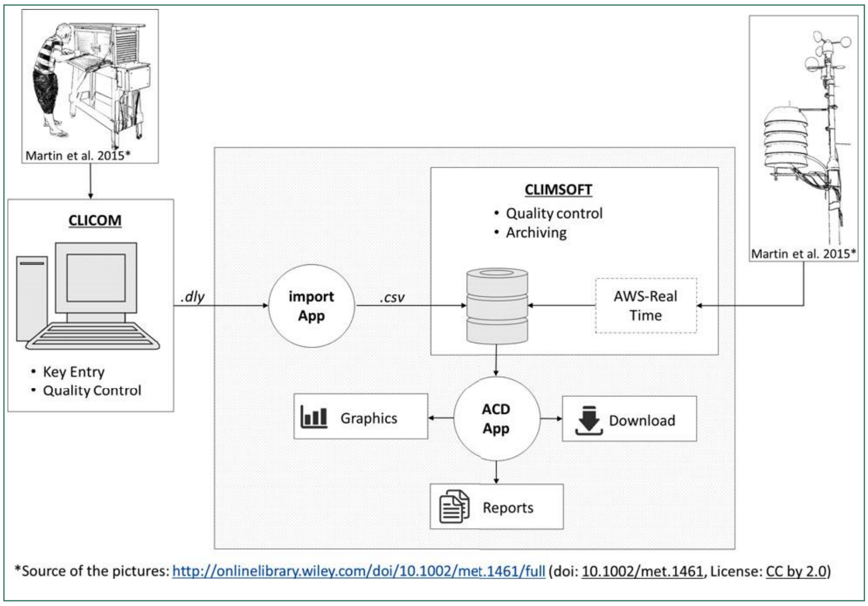

Figure 4: Data flow at ZMD. The CLIMSOFT database is the core of the CDMS, as it stores the data coming from the manual weather stations (left side) and the AWSs (right side). The ACD-App allows users to create different types of products using the data stored in the database.

Department of Meteorological Services, DMS, Botswana

Implementation of CDMS

At the beginning of the project, there was no properly functioning database at the DMS Botswana. No main database including all observational climate observations existed. Instead, the observational climate data were stored in several CLIMSOFT databases of different contents, with some of the information being redundant and other data missing.

In agreement with the department's management, the focus was set on installing CLIMSOFT version 4.0. As a second step it was necessary to incorporate all data from the different databases into the new main database system. Therefore, DMS got also involved in the development of CLIMSOFT version 4.0 by testing the new version and reporting bugs to the developers.

Additionally, the ACD-App was installed to allow for initial quality control of the data stored in CLIMSOFT, and the import-App to allow entry of historical climate observation into the new CLIMSOFT database. Monthly climatological data has been compiled using CLIMSOFT version 4.0 and transmitted to international data centres based on WMO standards using the global telecommunication system (GTS), a system of telecommunication facilities and arrangements for the rapid collection, exchange, and distribution of observations and processed information.

Data rescue

Data rescue started by collecting information about the quantity of paper documents at the DMS. These documents have been stored in three different archive rooms located in several buildings at the headquarters. However, none of the archives met the WMO requirements according to the WMO guidelines on "Best Practices for Climate Data Rescue" (WMO, 2016). To support DMS, it was necessary to get additional external funding. Support provided by the Global Climate Observing System made possible the reconditioning of these rooms by purchasing new shelves and more than 1,000 archiving boxes. Furthermore, this organization provided DMS with digitization equipment including two digital cameras and a scanner. Additional information on the data rescue activity carried out at DMS can be found on the webpage of the International Data Rescue portal (Riede, 2015, 2016). A former training room at the main building was rearranged to be used as an archive and digitizing room. Paper records were imaged using the new cameras and scanner. The resulting digital files were then stored on an external drive. In total, more than one million pages of climate documents are available for digitization. To support the data rescue processing, the keyEntry-App has been installed together with the import-App to import the entered data into the CLIMSOFT database.

Capacity Building

Similarly to INAMET, several training activities have been performed since 2014. The local staff have been trained in the use of the apps, in the open-source programming language employed to develop them, and in the CLIMSOFT software. Several training events on data rescue have also been carried out throughout the years of the project. The first training event addressed how to organize data rescue and the importance of historical climate data. The focus of the further training activities was on using the electronic equipment, storing the content in a digital format, and maintaining the archive.

Zambia Meteorological Department, ZMD, Zambia

Implementation of a CDMS

ZMD has been using the CLImate COMputing system, CLICOM (WMO, 1989) since the late 1980s as its CDMS. It was developed in 1985 by the National Oceanic and Atmospheric Administration of the United States as a PC-based database running on MS-DOS but it cannot be operated on the newer commercial operating systems (Martin et al., 2015).

Although CLICOM is running properly and kept up-to-date at ZMD, its low compatibility with modern operating systems makes it difficult to work with the climate database. It was therefore agreed that, with the support of SASSCAL, CLICOM should be replaced with a more modern CDMS. CLIMSOFT was identified to be the best solution since it has been already used at ZMD in the past.

The efforts have focused on the installation and use of CLIMSOFT in an operational mode. The software was installed in 2014, accompanied by a new data-flow scheme to ensure the appropriate storage of climate data (see Fig. 4). Since CLICOM has been running for over 30 years, it was agreed to run it in parallel with

CLIMSOFT to avoid any loss of data. In fact, data from manual weather stations are still being entered into CLICOM and then imported into CLIMSOFT. This import was done first with an open-source tool developed specifically for ZMD, although it has been replaced with the more reliable tool import-App.

In the same way as with INAMET, the observation data recorded by the AWS network of ZMD (including the stations from the SASSCAL network) are being transferred automatically into the CLIMSOFT database through the "AWS-Real time" feature.

The ACD-App developed in the framework of SASSCAL has been installed and is currently in use for quality control and downloading of the data.

Data rescue

ZMD is currently very active in data rescue activities. The Climate Information and Early Warning Systems (CIEWS) project was already supporting data rescue at ZMD (UNDP, 2012) when SASSCAL started. Therefore, it was agreed that SASSCAL would complement the efforts of CIEWS in this matter. Whereas CIEWS provides the meteorological service with data rescue equipment for digitization (e.g., computers, scanners, cameras), SASSCAL has focused on the reorganization of the archive by providing archive boxes and setting up a master plan for the allocation of the on-paper documents (see Fig. 5).

Capacity building

Similarly to INAMET, the training activities carried out since late 2014 were aimed at strengthening capacities in the management of climate data, especially those of the staff responsible for maintaining the CDMS. Therefore, training focused on basic concepts related to climate data, such as the relevance of metadata and its importance to identify inhomogeneities in a given dataset was carried out. In addition, staff were also trained in CLIMSOFT and an open-source computing language to facilitate future statistical analysis of the data (Tab. 2). As in the other countries, continuous support was provided by DWD to ensure the proper operation of CLIMSOFT and the apps and to ensure that the system could function sustainably.

Summary, conclusion and outlook

The SASSCAL initiative has served as a platform for the NMSs of Angola, Botswana, and Zambia to improve their management of climate data in a sustainable manner. DWD's collaboration and support of the technical staff aimed to ensure that the NMSs can operate and maintain the new data management system implemented in each country in the long term, even after the end of this cooperation. All partners have received at least six working visits by DWD staff during the project, which included training or technical support. Furthermore, remote assistance from Germany was provided to support the progress in data management and data rescue.

As a result, all countries are using CLIMSOFT as their core CDMS in an operational mode. To complement the CDMS, open-source tools have been developed to fulfil the specific needs of the NMSs in the region. These include the ACD-App (see Posada & Riede, 2018a); the keyEntry-App (see Posada & Riede, 2018b) and the import-App (see Posada & Riede, 2018c). The apps are freely available and open source so that end users with programming knowledge are able to modify the source code to implement new functionalities.

All actions taken are intended to provide a long-term and sustainable solution for the management of climate data by the NMSs. Although these actions were based on the specific needs and capacities of each service, some common challenges were identified:

- The activities should be communicated to all levels of the hierarchy (e.g., from the director to the technical staff). It was found that many persons were initially sceptical of the cooperation since many former projects had already provided tools and equipment that were not being used in the end. Therefore, a long-term collaboration that includes all levels of NMS staff is essential for introducting new climate products, especially in many African countries, where a lot of support is needed for running and maintaining these products.
- The maintenance of the data management systems relies mainly on the technical staff of the NMSs; as a result, high turnover of employees could lead to the breakdown of the system. To minimize the effects of such staffing fluctuations, the NMSs should keep complete

Figure 5: Data rescue activities in Botswana (left) and paper archive in Zambia (right): (a) before and (b) during the ongoing reorganization.

Climate

documentation of the processes related to climate data management so that the new staff can easily take over.

- Technical support of CLIMSOFT users is strongly recommended, especially for upgrading the software to the most recent version (version 4.0), so that the NMSs run the same CMDS version. This, in turn, could lead to an easy exchange of data between meteorological services in the future. The international exchange of climate data would be extremely beneficial for the region, for climate analysis and weather forecasts. This exchange is typically done through the WMO's global telecommunication system, but use of that system is limited among the NMS partners. Further support to the NMSs will be required to encourage the use of the system.
- Although data rescue activities are currently being carried out, there is still a great need for financial support (e.g., hiring temporary staff, purchasing archive boxes, maintaining paper archive) to complete these activities.

The results of this activity are a starting point for developing further observation-based climate services. Regularly updated time series of observations provide the basis for continuous climate monitoring (e.g., by providing monthly updates of climatological maps for the region). Creating monthly regional air temperature maps based on the SASSCAL AWS network was tested by Eiselt et al. (2017) (see Riede & Eiselt, 2018). This could be extended to other meteorological parameters, such as precipitation, and could serve as a basis for an online climatological information portal, as is already available for other geographical regions of the world (e.g., the German Climate Atlas) (Kaspar et al., 2013).

Finally, it should be noted that identifying synergies between ongoing international activities in the region would help optimize resources and achieve long-term sustainable solutions for the specific needs of national meteorological services. The SASSCAL activity presented here is an example of such an exchange between initiatives, as can be seen in the efforts in data rescue in the meteorological services of Botswana and Zambia. Other regional institutions, such as the Climate Services Centre of the Southern African Development Community (SADC), based in Gaborone, could be potential partners for future collaboration.

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References

Eiselt, K.-U., Kaspar, F., Mölg, T., Krähenmann, S., Posada, R. & Riede, J. (2017). Evaluation of gridding procedures for air temperature over Southern Africa. *Advances in Science and Research*, **14,** 163–173. doi: 10.5194/asr-14-163-2017

Hahn, C. J. & Warren, S. G. (2009). Extended edited cloud reports from ships and land stations over globe, 1952–1996 (2009 update). *Carbon Dioxide Information Analysis Center.* doi: 10.3334/CDIAC/cli.ndp026c

Hänsler, A. (2014). *Minutes – SASSCAL Thematic Workshop Climate*. Available at http://www.sasscal.org/downloads/Minutes_SASSCAL-ClimateWorkshop_August2014_FINAL.pdf (last accessed 7 July 2017)

Kaspar, F., Helmschrot, J., Mhanda, A., et al. (2015a). The SASSCAL contribution to climate observation, climate data management and data rescue in Southern Africa. *Advances in Science and Research*, **12,** 171–177. doi: 10.5194/asr-12-171-2015

Kaspar, F., Tinz, B., Mächel, H. & Gates, L. (2015b). Data rescue of national and international meteorological observations at Deutscher Wetterdienst. *Advances in Science and Research*, **12,** 57–61. https://doi.org/10.5194/asr-12-57-2015

Kaspar, F., Müller-Westermeier, G., Penda, E., Mächel, H., Zimmermann, K., Kaiser-Weiss, A. & Deutschländer, T. (2013). Monitoring of climate change in Germany – data, products and services of Germany's National Climate Data Centre. *Advances in Science and Research*, **10,** 99–106. https://doi.org/10.5194/asr-10-99-2013

Lawrimore, J. H., Menne, M. J., Gleason, B. E., Williams, C. N., Wuertz, D. B., Vose, R. S. & Rennie, J. (2011). An overview of the Global Historical Climatology Network monthly mean temperature data set, version 3. *Journal of Geophysical Research*, **116** (D19121), 1–18. doi:10.1029/2011JD016187

Martin, D. J., Howard, A., Hutchinson, R., McGree, S. & Jones, D.A. (2015). Development and implementation of a climate data management system for western Pacific small island developing states. *Meteorological Applications*, **22,** 273–287. doi:10.1002/met.1461

Menne, M. J., Durre, I., Korzeniewski, B., McNeal, S., Thomas, K., Yin, X., Anthony, S., Ray, R., Vose, R.S., Gleason, B.E. & Houston, T.G. (2012a). Global Historical Climatology Network - Daily (GHCN-Daily), Version 3.20. NOAA National Climatic Data Center. doi:10.7289/V5D21VHZ

Menne, M. J., Durre, I., Vose, R. S., Gleason, B.E. & Houston, T.G. (2012b). An overview of the Global Historical Climatology Network daily database. *Journal of Atmospheric and Oceanic Technology*, **29,** 897–910. doi:10.1175/JTECH-D-11-00103.1

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: present state, challenges, and achievements of the regional climatic observation network and database. This volume.

Peterson, T.C. & Vose, R.S. (1997). An overview of the Global Historical Climatology Network temperature database. *Bulletin of the American Meteorological Society*, **78**, 2837–2849.

Posada, R., Nascimento, D., Neto, F.O.S., Riede, J., & Kaspar, F. (2016). Improving the climate data management in the meteorological service of Angola: experience from SASSCAL. *Advances in Science and Research*, **13,** 97–105. doi: 10.5194/asr-13-97-2016

Posada, R. & Riede, J. (2018a). Analysis of Climate Data Application (ACD-App). This volume

Posada, R. & Riede, J. (2018b). Key Entry Form Application to digitize climate data (keyEntry-App). This volume

Posada, R. & Riede, J. (2018c). Application to import climate data into CLIMSOFT (import-App). This volume

Riede, J. (2015). Climate data rescue implementation plan for the Department of Meteorological Services Botswana. WMO, International Data Rescue Portal. Available online at https://idare-portal.org/sites/default/files/DARE_Botswana_Recommendation.pdf (last accessed 3 July 2017)

Riede, J. (2016). Climate data rescue progress report, Department of Meteorological Services Botswana. WMO, International Data Rescue Portal. Available online at https://idare-portal.org/sites/default/files/2016DARE_Botswana.pdf (last accessed 3 July 2017)

Riede, J. & Eiselt, K.U. (2018). Gridded maps of climate data for southern Africa. This volume

Stuber, D., Mhanda, A. & Lefebvre, C. (2011). Climate data management systems: status of implementation in developing countries. *Climate Research*, **47,** 13–20. doi:10.3354/cr00961

Thorne, P.W., Willett, K.M., Allan, R.J., et al. (2011). Guiding the creation of a comprehensive surface temperature resource for twenty-first-century climate science. *Bulletin of the American Meteorological Society*, **92,** ES40–ES47. http://dx.doi.org/10.1175/2011BAMS3124.1

Tan, L.S., Burton, S., Crouthamel, R., van Engelen, A., Hutchinson, R., Nicodemus, Peterson, T.C. & Rahimzadeh, F. (2004). *Guidelines on climate data rescue*. WMO/TD no. 1210. Geneva: World Meteorological Organization

United Nations Development Programme (UNDP) (2012). Strengthening climate information and early warning systems in Zambia. Description available at http://adaptation-undp.org/projects/ldcf-ews-zambia (last accessed 27 June 2017)

United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA) (2016). Overview of El Niño response in East and Southern Africa. Available at http://www.unocha.org/sites/dms/Documents/2016_11_El-nino_Africa_Breakfast_meeting_FINAL.pdf (last accessed 5 February 2018)

World Meteorological Organization (WMO) (2014). *Climate data management system specifications*. WMO no. 1131. Geneva: World Meteorological Organization. Available at http://library.wmo.int/pmb_ged/wmo_1131_en.pdf (last accessed 7 July 2017)

WMO (2016). *Guidelines on best practices for climate data rescue*. WMO no. 1182. Geneva: World Meteorological Organization. Available at https://library.wmo.int/opac/doc_num.php?explnum_id=3318 (last accessed 7 July 2017)

WMO (1989). CLICOM Project (climate data management system). WMO/TD no. 299. Geneva: World Meteorological Organization. Available at https://library.wmo.int/pmb_ged/wmo-td_299_en.pdf (last accessed 7 July 2017)

References [CrossRef]

Eiselt, K.-U., Kaspar, F., Mölg, T., Krähenmann, S., Posada, R. & Riede, J. (2017). Evaluation of gridding procedures for air temperature over Southern Africa. *Advances in Science and Research*, **14,** 163–173. CrossRef

Hahn, C. J. & Warren, S. G. (2009). Extended edited cloud reports from ships and land stations over globe, 1952–1996 (2009 update). *Carbon Dioxide Information Analysis Center*. CrossRef

Hänsler, A. (2014). *Minutes – SASSCAL Thematic Workshop Climate*. Available at http://www.sasscal.org/downloads/Minutes_SASSCAL-ClimateWorkshop_August2014_FINAL.pdf (last accessed 7 July 2017)

Kaspar, F., Helmschrot, J., Mhanda, A., et al. (2015a). The SASSCAL contribution to climate observation, climate data management and data rescue in Southern Africa. *Advances in Science and Research*, **12,** 171–177. CrossRef

Kaspar, F., Tinz, B., Mächel, H. & Gates, L. (2015b). Data rescue of national and international meteorological observations at Deutscher Wetterdienst. *Advances in Science and Research*, **12,** 57–61. CrossRef

Kaspar, F., Müller-Westermeier, G., Penda, E., Mächel, H., Zimmermann, K., Kaiser-Weiss, A. & Deutschländer, T. (2013). Monitoring of climate change in Germany – data, products and services of Germany's National Climate Data Centre. *Advances in Science and Research*, **10,** 99–106. CrossRef

Lawrimore, J. H., Menne, M. J., Gleason, B. E., Williams, C. N., Wuertz, D. B., Vose, R. S. & Rennie, J. (2011). An overview of the Global Historical Climatology Network monthly mean temperature data set, version 3. *Journal of Geophysical Research*, **116** (D19121), 1–18. CrossRef

Martin, D. J., Howard, A., Hutchinson, R., McGree, S. & Jones, D.A. (2015). Development and implementation of a climate data management system for western Pacific small island developing states. *Meteorological Applications*, **22,** 273–287. CrossRef

Menne, M. J., Durre, I., Korzeniewski, B., McNeal, S., Thomas, K., Yin, X., Anthony, S., Ray, R., Vose, R.S., Gleason, B.E. & Houston, T.G. (2012a). Global Historical Climatology Network - Daily (GHCN-Daily), Version 3.20. NOAA National Climatic Data Center. CrossRef

Menne, M. J., Durre, I., Vose, R. S., Gleason, B.E. & Houston, T.G. (2012b). An overview of the Global Historical Climatology Network daily database. *Journal of Atmospheric and Oceanic Technology*, **29,** 897–910. CrossRef

Muche, G., Kruger, S., Hillmann, T. et al. (2018)SASSCAL WeatherNet: history, state of Measuring Network, database and online presentation, challenges & success. This volume. CrossRef

Peterson, T.C. & Vose, R.S. (1997). An overview of the Global Historical Climatology Network temperature database. *Bulletin of the American Meteorological Society*, **78**, 2837–2849. CrossRef

Posada, R., Nascimento, D., Neto, F.O.S., Riede, J., & Kaspar, F. (2016). Improving the climate data management in the meteorological service of Angola: experience from SASSCAL. *Advances in Science and Research*, **13,** 97–105. CrossRef

Posada, R. & Riede, J. (2018a). Analysis of Climate Data Application (ACD-App). This volume. CrossRef

Posada, R. & Riede, J. (2018b). Key Entry Form Application to digitize climate data (keyEntry-App). This volume. CrossRef

Posada, R. & Riede, J. (2018c). Application to import climate data into CLIMSOFT (import-App). This volume. CrossRef

Riede, J. (2015). Climate data rescue implementation plan for the Department of Meteorological Services Botswana. WMO, International Data Rescue Portal. Available online at https://idare-portal.org/sites/default/files/DARE_Botswana_Recommendation.pdf (last accessed 3 July 2017)

Riede, J. (2016). Climate data rescue progress report, Department of Meteorological Services Botswana. WMO, International Data Rescue Portal. Available online at https://idare-portal.org/sites/default/files/2016DARE_Botswana.pdf (last accessed 3 July 2017)

Riede, J. & Eiselt, K.U. (2018). Gridded maps of climate data for southern Africa. This volume. CrossRef

Stuber, D., Mhanda, A. & Lefebvre, C. (2011). Climate data management systems: status of implementation in developing countries. *Climate Research*, **47,** 13–20. CrossRef

Thorne, P.W., Willett, K.M., Allan, R.J., et al. (2011). Guiding the creation of a comprehensive surface temperature resource for twenty-first-century climate science. *Bulletin of the American Meteorological Society*, **92,** ES40–ES47. CrossRef

Tan, L.S., Burton, S., Crouthamel, R., van Engelen, A., Hutchinson, R., Nicodemus, Peterson, T.C. & Rahimzadeh, F. (2004). *Guidelines on climate data rescue*. WMO/TD no. 1210. Geneva: World Meteorological Organization

United Nations Development Programme (UNDP) (2012). Strengthening climate information and early warning systems in Zambia. Description available at http://adaptation-undp.org/projects/ldcf-ews-zambia (last accessed 27 June 2017)

United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA) (2016). Overview of El Niño response in East and Southern Africa. Available at http://www.unocha.org/sites/dms/Documents/2016_11_Elnino_Africa_Breakfast_meeting_FINAL.pdf (last accessed 5 February 2018)

World Meteorological Organization (WMO) (2014). *Climate data management system specifications*. WMO no. 1131. Geneva: World Meteorological Organization. Available at http://library.wmo.int/pmb_ged/wmo_1131_en.pdf (last accessed 7 July 2017)

WMO (2016). *Guidelines on best practices for climate data rescue*. WMO no. 1182. Geneva: World Meteorological Organization. Available at https://library.wmo.int/opac/doc_num.php?explnum_id=3318 (last accessed 7 July 2017)

WMO (1989). CLICOM Project (climate data management system). WMO/TD no. 299. Geneva: World Meteorological Organization. Available at https://library.wmo.int/pmb_ged/wmo-td_299_en.pdf (last accessed 7 July 2017)

Analysis of Climate Data Application (ACD-App)

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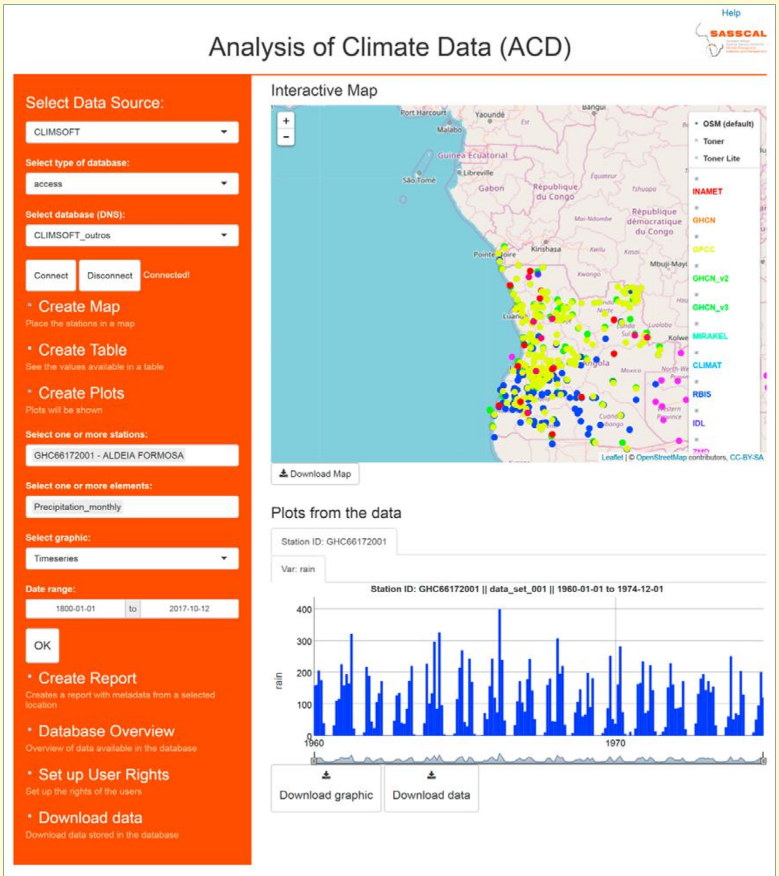

Figure 1: Screenshot ACD-App interface when CLIMSOFT is selected as data source. Here two of the features available are shown: (1) the map with the location of the weather stations and (2) the time series of precipitation for one Angolan weather station. In order to plot these graphics, the data have to be already available in the CLIMSOFT database.

To support the NMSs in regard to data quality management, we developed an open-source tool called Analysis of Climate Data Application (ACD-App) that allows users to interact with data archived in any CLIMSOFT database. The ACD-App was developed using Shiny, an open-source R package that provides a web framework for building web applications with R (https://shiny.rstudio.com). Its main aim was to facilitate qualitative quality control checks of climate datasets through a graphical visualization of climate data. However, the app has been improved over the years so that it also allows users to download of data from any CLIMSOFT database, create metadata reports of these data, and even create graphics from data stored in external ASCII files. Therefore, the ACD-App enables users to choose between working with data stored in a CLIMSOFT database or in an external ASCII file. If the first option is selected, users will be asked to connect to the CLIMSOFT database and, depending on the app-specific user rights, they will be able to (1) create a map that locates the weather stations, (2) download the climate data of one or more stations, (3) create PDF reports with metadata for a given location, (4) create graphics such as time series, histograms, or wind roses, (5) get an overview of the whole database, or (6) control the user rights for the ACD-App. Figure 1 shows a screenshot of the ACD-App with the options available when a user connects to a CLIMSOFT database.

Users who select the second option of an external file will be able to create graphics or download data stored in a text file (.txt) or comma-separated file (.csv). For the app to recognize the data, the file should contain, at least, the information related to (1) the station identifier, (2) the date or date and time at which the observation was done, and (3) the observation values of one or more elements (e.g., maximum temperature). A screenshot of the ACD-App once the external file option has been selected can be found in Figure 2. The ACD-App has been hosted in GitHub – an online code-hosting repository based on the GIT version control system (Dabbish et al., 2012) for download and further development: https://github.com/sasscal-dwd-apps/ACD-App. A detailed manual on how to install it and how to use it can be found here: https://sasscal-dwd-apps.github.io/ACD-App/en/documentation.html

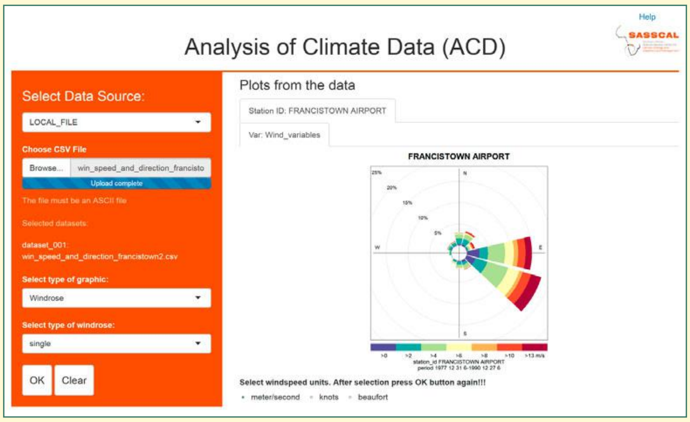

Figure 2: Screenshot ACD-App interface when a local file is selected as data source. Here the wind rose for a Botswanan weather station is shown. In order to plot these graphics, the data should be saved in a file with ASCII format and include, at least, the station name or identifier, the date of measurement, and the observed values.

Key Entry Form Application to digitize climate data (keyEntry-App)

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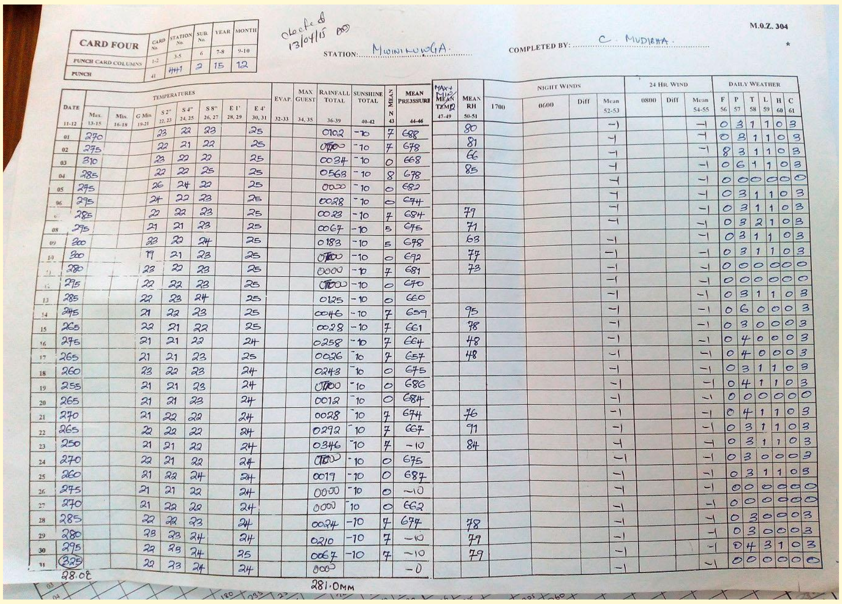
A frequent issue at the NMSs was the entry of on-paper climate data. CLIMSOFT provides some templates for entering data directly into the databases, but these templates often do not satisfy the requirements of meteorological services. Therefore, an additional open-source tool was designed to facilitate data entry in the partner countries. The app provides users with a web-based interface to enter the data in the same way that they are structured on the on-paper form (Fig. 1). Users can also customize the structure of the forms and create their own templates. It also includes a quality control of absolute limits that checks the meteorological data as they are entered and alerts users if an entered value is implausible.

Similarly to the ACD-App, the keyEntry-App has been developed using Shiny so that it can easily be run on any PC with a web browser. It has also been hosted on GitHub for download and further development: https://github.com/sasscal-dwd-apps/keyEntry-App. A detailed manual on how to install the app and how to use it can be found here: https://sasscal-dwd-apps.github.io/keyEntry-App/en/documentation.html



Key Entry App

ZAMBIA METEOROLOGICAL DEPARTMENT

SASSCAL Southern African Science Service Centre for Climate Change and Adaptive Land Management

Help

Met. Service: zmd | Form: MOZ304A | Station No.: 441 | Year: 2015 | Month: 12 | Station Id: MWINIL01 - MWINILUNGA MET | Complemented by: rp | Create

Key Entry Form | Limits & Scale Factors

	Temp. Max	Temp. min	G Min	S 2	S 4	S 8	E 1	E 4	Mean DP	MAX GUST	RAIN. TOTAL	SUNS. TOTAL	N MEAN	MEAN PRESS.	MEAN TEMP.	MEAN RH.	WIND 1700	WIND 0600	WIND Diff	WIND Mean	24Hr. WIND 0800	24Hr. WIND Diff	24Hr. WIND Mean	F	P	T	L	H	C	EVAP
01	270	NA	NA	23	22	23	NA	NA	25	NA	102	-10	7	9688	NA	80	NA	NA	NA	NA	NA	NA	NA	0	3	1	1	0	3	NA
02	275	NA	NA	22	21	22	NA	NA	25	NA	0	-10	7	9678	NA	81	NA	NA	NA	NA	NA	NA	NA	0	3	1	1	0	3	NA
03	310	NA	NA	23	22	22	NA	NA	25	NA	34	-10	0	9668	NA	66	NA	NA	NA	NA	NA	NA	NA	8	3	1	1	0	3	NA
04	285	NA	NA	22	22	25	NA	NA	25	NA	563	-10	8	9678	NA	85	NA	NA	NA	NA	NA	NA	NA	0	6	1	1	0	3	NA
05	275	NA	NA	26	24	22	NA	NA	25	NA	0	-10	0	9682	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0	0	0	0	0	NA
06	295	NA	NA	24	22	23	NA	NA	25	NA	NA	-10	0	9674	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	3	1	1	0	3	NA
07	285	NA	NA	22	22	23	NA	NA	25	NA	NA	-10	7	9684	NA	79	NA	NA	NA	NA	NA	NA	NA	0	3	1	1	0	3	NA
08	295	NA	NA	21	21	23	NA	NA	25	NA	NA	-10	5	9675	NA	71	NA	NA	NA	NA	NA	NA	NA	0	3	2	1	0	3	NA
09	300	NA	NA	23	22	24	NA	NA	25	NA	NA	-10	5	9678	NA	63	NA	NA	NA	NA	NA	NA	NA	0	3	1	1	0	3	NA
10	300	NA	NA	19	21	23	NA	NA	25	NA	NA	-10	0	9692	NA	77	NA	NA	NA	NA	NA	NA	NA	0	3	1	1	0	3	NA
11	280	NA	NA	23	22	23	NA	NA	25	NA	NA	-10	7	9681	NA	73	NA	NA	NA	NA	NA	NA	NA	0	0	0	0	0	0	NA
12	295	NA	NA	22	22	23	NA	NA	25	NA	NA	-10	0	9670	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0	0	0	0	0	NA
13	285	NA	NA	22	23	24	NA	NA	25	NA	NA	-10	0	9660	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	3	1	1	0	3	NA
14	245	NA	NA	21	22	23	NA	NA	25	NA	NA	-10	7	9659	NA	95	NA	NA	NA	NA	NA	NA	NA	0	6	0	0	0	3	NA
15	265	NA	NA	22	21	22	NA	NA	25	NA	NA	-10	7	9661	NA	78	NA	NA	NA	NA	NA	NA	NA	0	3	0	0	0	3	NA
16	275	NA	NA	21	21	22	NA	NA	24	NA	NA	-10	7	9664	NA	48	NA	NA	NA	NA	NA	NA	NA	0	4	0	0	0	3	NA
17	265	NA	NA	21	21	23	NA	NA	25	NA	NA	-10	7	9657	NA	48	NA	NA	NA	NA	NA	NA	NA	0	4	0	0	0	3	NA
18	260	NA	NA	23	22	23	NA	NA	24	NA	NA	-10	0	9675	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	3	1	1	0	3	NA
19	255	NA	NA	21	21	23	NA	NA	24	NA	NA	-10	0	9686	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	4	1	1	0	3	NA
20	265	NA	NA	21	21	23	NA	NA	24	NA	NA	-10	0	9684	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0	0	0	0	0	NA
21	270	NA	NA	21	22	22	NA	NA	24	NA	NA	-10	7	9674	NA	76	NA	NA	NA	NA	NA	NA	NA	0	4	1	1	0	3	NA
22	265	NA	NA	22	22	22	NA	NA	24	NA	NA	-10	7	9667	NA	91	NA	NA	NA	NA	NA	NA	NA	0	3	1	1	0	3	NA
23	250	NA	NA	21	21	22	NA	NA	24	NA	NA	-10	7	NA	NA	84	NA	NA	NA	NA	NA	NA	NA	0	3	1	1	0	3	NA
24	270	NA	NA	22	21	22	NA	NA	24	NA	NA	-10	0	9675	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	3	0	NA	0	3	NA
25	260	NA	NA	21	22	24	NA	NA	24	NA	NA	-10	0	9687	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	3	1	NA	0	3	NA
26	275	NA	NA	21	21	22	NA	NA	24	NA	NA	-10	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0	0	NA	0	0	NA
27	270	NA	NA	21	22	22	NA	NA	24	NA	NA	-10	0	9662	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0	0	NA	0	0	NA
28	285	NA	NA	22	22	23	NA	NA	24	NA	NA	-10	7	9677	NA	78	NA	NA	NA	NA	NA	NA	NA	0	3	0	NA	0	3	NA
29	280	NA	NA	23	23	24	NA	NA	24	NA	NA	-10	7	NA	NA	79	NA	NA	NA	NA	NA	NA	NA	0	3	0	NA	0	3	NA
30	295	NA	NA	22	23	24	NA	NA	25	NA	NA	-10	7	NA	NA	79	NA	NA	NA	NA	NA	NA	NA	0	4	3	NA	0	3	NA
31	325	NA	NA	22	23	24	NA	NA	24	NA	NA	-10	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0	0	NA	0	0	NA
MAX.	325	NA	NA	26	24	25	NA	NA	25	NA	563	-10	8	9692	NA	95	NA	NA	NA	NA	NA	NA	NA	8	6	3	1	0	3	NA
MIN.	245	NA	NA	19	21	22	NA	NA	24	NA	0	-10	0	9657	NA	48	NA	NA	NA	NA	NA	NA	NA	0	0	0	0	0	0	NA
SUM	8625	NA	NA	680	677	710	NA	NA	761	NA	699	-310	116	251536	NA	1431	NA	NA	NA	NA	NA	NA	NA	8	83	20	15	0	72	NA
MEAN	278.2	NA	NA	21.9	21.8	22.9	NA	NA	24.5	NA	139.8	-10	3.9	9674.5	NA	75.3	NA	NA	NA	NA	NA	NA	NA	0.3	2.7	0.6	0.7	0	2.3	NA

Calculate values | Save data | Download as '.csv' | Download as '.xls' | Send data per E-Mail

Figure 1: (top) Original form and (bottom) digital form of ZMD. The digital form maintains the same structure as the on-paper form to facilitate data entry. It also provides embedded quality control, flagging the values entered that are outside a given threshold.

Application to import climate data into CLIMSOFT (import-App)

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An important challenge that the national meteorological services were facing in the beginning of the project was the importation of data already available in electronic form into CLIMSOFT. To overcome this issue, SASSCAL provided different open-source tools created specifically for each meteorological service. Over the years, however, it was acknowledged that a common tool would be a better solution to ensure the long-term operation of the import process. Therefore, the SASSCAL team developed a new open-source application called import-App, which is currently available to all NMS partners.

The app provides users with different import options. Two of these options are common to all NMS partners:

-
- – From a key-entry form: This option allows users to import data entered with the keyEntry-App.
- – From a CLIMSOFT database: This option allows the importation of data from one CLIMSOFT database to another. Specific features were developed for INAMET and ZMD to make the importation of data stored in specific file formats possible. Therefore, the app allows INAMET to import data entered in old electronic spreadsheets, whereas ZMD can import the data stored in the CLICOM system. Figure 1 shows screenshots of the different options currently available in the app.

The import-App is hosted on GitHub for download and further development: https://github.com/sasscal-dwd-apps/import-App. A detailed manual on how to install it and how to use it can be found here: https://sasscal-dwd-apps.github.io/import-App/en/documentation.html

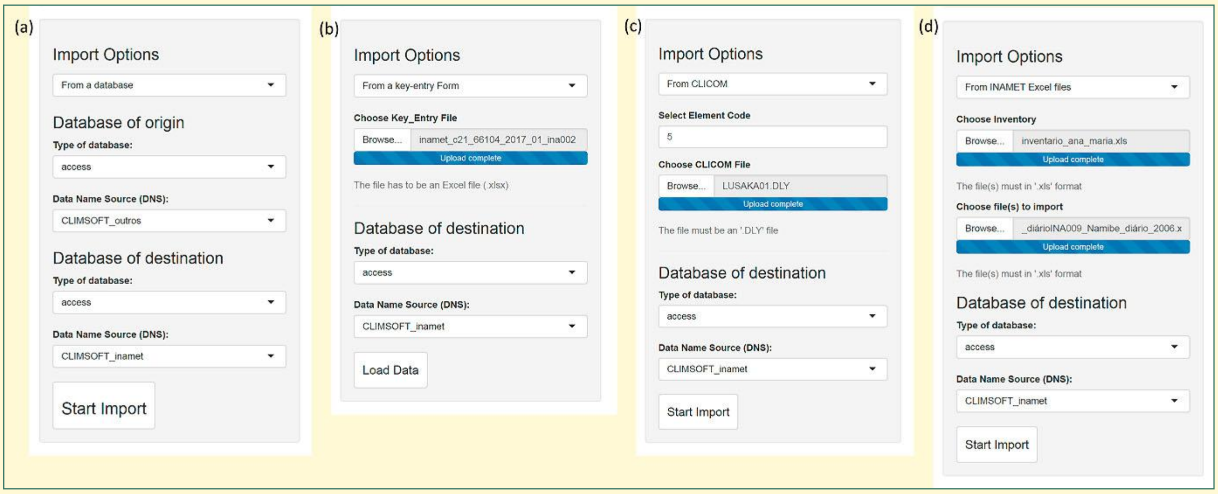

Figure 1: Screenshots of the different features available in the import-App when users select the importation of data (a) from a CLIMSOFT database, (b) from CLICOM (available only at ZMD), (c) from a key-entry form, or (d) from older INAMET electronic spreadsheets.

Gridded maps of climate data for southern Africa

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Climate

Interpolation of meteorological data from SASSCAL-WeatherNet (Muche et al., 2018) observational land surface stations provides additional information for a data-sparse region. As an application example, different spatial interpolation methods for maximum and minimum temperature have been tested to produce a gridded dataset for the SASSCAL region. We tested the interpolation for the time period of September 2014 to August 2016, as this period had the highest availability of observational temperature data. The best interpolation was achieved by combining multiple linear regression (elevation, a continentality index, and latitude as predictors) with three-dimensional inverse distance weighting (Eiselt et al., 2017).

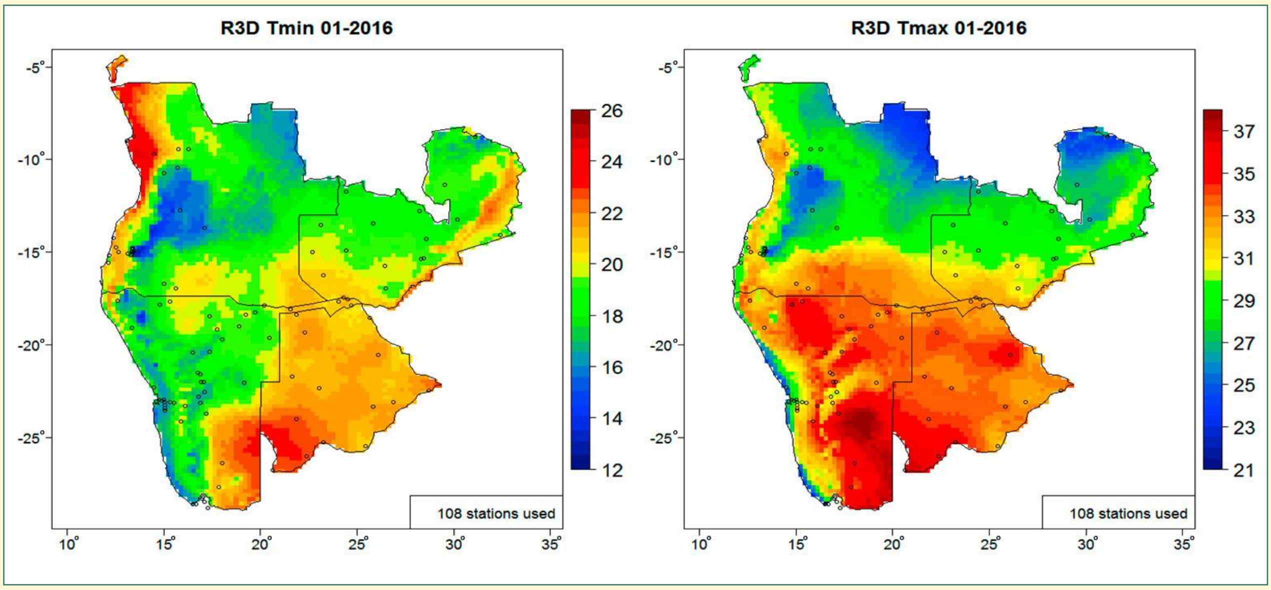

Figure 1: Application example for the month of January 2016, with a three-dimensional interpolation of minimum temperature (Tmin, left) and maximum temperature (Tmax, right). The best predictors of the model were elevation, continentality index, and latitude. The locations of the AWS of SASSCAL are indicated by circles.

References:

Eiselt, K.-U., Kaspar, F., Mölg, T., Krähenmann, S., Posada, R. & Riede, J. (2017). Evaluation of gridding procedures for air temperature over Southern Africa. *Advances in Science and Research*, **14,** 163–173. doi: 10.5194/asr-14-163-2017

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: present state, challenges, and achievements of the regional climatic observation network and database. This volume.

Climate

SASSCAL WeatherNet: present state, challenges, and achievements of the regional climatic observation network and database

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Abstract: Automatic weather stations (AWSs) serve a number of goals in the SASSCAL context and beyond. A sufficient cover and density in geographical space is needed to record spatial climatic variability and to feed climate models and forecast services. In addition, research projects using an ecosystem approach require robust information on local weather. In response to these goals and under consideration of the low density of climate stations in the SASSCAL region (Angola, Botswana, Namibia, South Africa, and Zambia), the establishment of a network of weather stations was initiated in 2009–2010. The SASSCAL network, meanwhile, includes 154 AWSs and has achieved a reputation for providing unprecedented progress in terms of coverage and access to climatic data for the SASSCAL region. This paper presents the most important strategic and technical steps, from setting up the station network for data transmission and data quality controls to the Internet publication of the SASSCAL WeatherNet climatic data.

Resumo: As estações meteorológicas automáticas (AWSs) servem uma série de fins no contexto do SASSCAL e mais além. São necessárias uma cobertura e densidade suficientes no espaço geográfico para registar a variabilidade espacial climática e alimentar os modelos climáticos e serviços de previsão. Além disso, projectos de investigação que usam uma abordagem ecossistémica requerem informação robusta sobre as condições meteorológicas locais. Em resposta a estes objectivos, e considerando a baixa densidade de estações climáticas na região do SASSCAL (Angola, Botswana, Namíbia, África do Sul e Zâmbia), foi iniciado o estabelecimento de uma rede de estações meteorológicas em 2009-2010. Entretanto, a rede do SASSCAL inclui 154 AWSs e alcançou uma reputação de proporcionar progresso sem precedentes em termos de cobertura e acesso a dados climáticos para a região do SASSCAL. Este artigo apresenta as etapas estratégicas e técnicas mais importantes, desde a criação da rede de estações para a transmissão e controlo da qualidade dos dados até à publicação online dos dados climáticos da SASSCAL WeatherNet.

Introduction

The Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) is a joint initiative of Angola, Botswana, Namibia, South Africa, Zambia, and Germany in response to the challenges of global change. SASSCAL research activities aim at improving our knowledge on the complex interactions and feedbacks between terrestrial and atmospheric systems. To better understand and assess processes, fluxes, and linkages in and between the systems, reliable data of high quality are needed. This is especially important considering climate variability and its projected change as well as socio-economic development in sub-Saharan Africa. However, a major challenge faced by most countries of southern Africa is the lack of adequate monitoring networks to provide reliable data, specifically for the development of efficient management strategies for sustainable water and land resources management, drought and flood risk analyses and forecasts, and climate change impact assessments. For example, in Angola, Botswana, and Zambia there is a demand for improving existing national weather-monitoring networks to provide up-to-date information for decision-makers and the public. By implementing and operating the SASSCAL WeatherNet, SASSCAL addresses this deficiency and has extended the national monitoring networks to provide a consistent and freely accessible dataset for the SASSCAL region.

The SASSCAL WeatherNet, with its currently 154 automatic weather stations (AWSs), and the necessary IT infrastructure for data transfer and open-access presentation on the Internet have been established only within the past seven years (2010–2017). This could be achieved only by a direct SASSCAL investment of approximately 1.3 Million € and the work of a team of six to ten staff members involved on a permanent or temporary basis.

History

The SASSCAL AWSs have been installed at different stages during the SASSCAL initiative. The first installations date back to 2010, replacing earlier devices (Jürgens et al., 2010). In 2013, a workshop was held in Windhoek, Namibia, to systematically expand the network with the participation of national meteorological services, ministries, World Meteorological Organization (WMO) representatives, scientists, and representatives of the funding agency to assess the current situation and identify the most pressing needs. A basic set of sensors, according to WMO standards, was decided upon for each station. One result of the workshop was the implementation of ten stations each in Angola, Botswana, and Zambia. The locations were suggested by the respective national meteorological services. Basics were decided upon for the open-access availability of data.

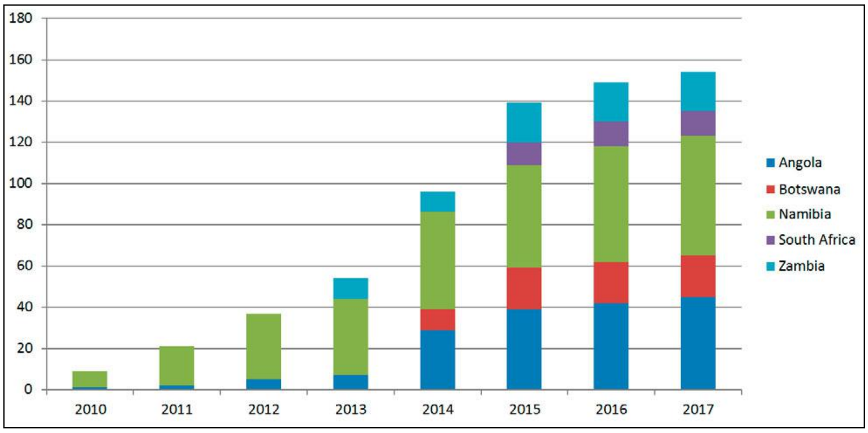

Figure 1: Implementation of automatic weather stations within SASSCAL WeatherNet. Row: cumulative number of AWSs per country; column: first data

Over the years, the network has been expanded in stages (Fig. 1). Many of these stations were financed from funds earmarked for SASSCAL, some of them directly for the purchase of equipment, and others through efforts in individual projects such as SASSCAL Task 001, Task 054, and Task 337.

Other donors have also participated, convinced by the possibilities of SASSCAL WeatherNet (BIOTA AFRICA; Ministry of Agriculture, Water and Forestry (MAWF), Namibia; Local Institutions in Globalized Societies [LINGS], Germany; Instituto Nacional de Meteorologia de Angola [INAMET], Angola; Instituto de Desenvolvimento Florestal [IDF], Angola; Instituto de Desenvolvimento Agrário [IDA], Angola; Universidade José Eduardo dos Santos [UJES], Angola; Gestão de Terras Aráveis [Gesterra], Angola; Gabinete para a Administração da Bacia Hidrográfica do rio Cunene [GABHIC], Angola; University of Basel, Switzerland).

The implementation of the AWSs has been done in several campaigns with a team of technicians from providers as well as from SASSCAL participants. All the IT components (data transmission pathways, algorithms for quality control, SASSCAL WeatherNet website design) have been set up by three staff members at the University of Hamburg. Maintenance of the stations in the field was carried out by only three staff members in Namibia, three staff members in South Africa, two staff members each in Angola, and the national weather services in Botswana and Zambia. In 2017, a second workshop with the participants of the SASSCAL WeatherNet was organised to gather the experiences had so far and to plan necessary steps for the future. For a sustainable future SASSCAL WeatherNet, it will be necessary to either integrate the stations into the maintenance networks of the national meteorological services or to increase the available trained maintenance staff within SASSCAL structures.

Technical implementation

Stations

At the end of 2017, the SASSCAL WeatherNet AWSs are distributed in the five countries of the SASSCAL region (see Tab. 1 and 2, Fig. 2). Currently, 88 stations have been purchased with SASSCAL funding and 66 stations were contributed

Climate

Table 1: List of weather stations and time series properties as at end of 2017

Name	Country	Latitude	Longitude	Altitude [m]	Type	WMO	Transmission	Air temperature	Soil temperature	Wind	Rain	Relative humidity	Barometric pressure	Solar irradiance	Leaf wetness	Fog precipitation	Soil moisture	Sunshine duration	Dew point	Wet bulb	First data	Status/Last data
Açucareira	Angola	-8.59100	13.60400	14	Adcon/OTT		GPRS	x		x	x	x		x							01.11.2017	active
Alto Dondo	Angola	-9.68333	14.46667	185	INOVA		GPRS	x	x	x	x	x	x	x	x				x		14.04.2014	undetermined
Barragem das Neves	Angola	-14.95200	13.36300	2074	Adcon/OTT		GPRS	x		x	x	x	x	x							19.10.2014	active
Benfica	Angola	-9.00000	13.09100	70	Adcon/OTT		GPRS	x		x	x	x		x							10.10.2009	active
Bentiaba	Angola	-14.25700	12.38700	11	Adcon/OTT		GPRS	x		x	x	x	x	x							27.10.2014	active
Bibala	Angola	-14.80800	13.34100	1061	Adcon/OTT		GPRS	x		x	x	x	x	x							21.10.2014	active
Cacuso	Angola	-9.42808	15.74621	1064	INOVA		GPRS	x		x	x	x	x	x							15.04.2014	09.03.2016 (1)
Caiundo	Angola	-16.41440	17.82000	1204	Adcon/OTT		GPRS														-	(1)
Campus ISPT	Angola	-14.95800	13.44500	2047	Adcon/OTT		GPRS	x		x	x	x	x	x							17.10.2014	active
Caope	Angola	-8.75500	13.42300	21	Adcon/OTT		GPRS	x	x	x	x	x		x							01.01.2016	active
Capangombe	Angola	-15.09600	13.13800	535	Adcon/OTT		GPRS	x		x	x	x	x	x							22.10.2014	active
Caraculo	Angola	-15.01900	12.65800	470	Adcon/OTT		GPRS	x		x	x	x	x	x							24.10.2014	active
Chianga (Huambo)	Angola	-12.74349	15.82923	1695	INOVA		GPRS	x	x	x	x	x	x	x	x				x		13.04.2014	undetermined
Cuito Cuanavale	Angola	-15.18150	19.17833	1214	INOVA		GPRS	x	x	x	x	x	x	x	x				x		15.08.2014	undetermined
Cusseque	Angola	-13.71000	17.10000	1529	Adcon/OTT		GPRS	x	x	x	x	x	x	x							27.03.2015	inactive
Damba	Angola	-6.68333	14.13333	602	INOVA		GPRS	x	x	x	x	x	x	x	x				x		28.04.2014	inactive
Espinheira	Angola	-16.77577	12.34777	448	Adcon/OTT		SAT	x	x	x	x	x	x	x		x	x				20.10.2015	active
Fazenda Pongo-Andongo 2	Angola	-9.64400	15.49100	1072	Adcon/OTT		GPRS	x	x	x	x	x		x							20.06.2011	inactive
Flamingos Bay	Angola	-15.56784	12.02124	13	Adcon/OTT		MAN	x			x	x				x					13.10.2017	active
Gambos	Angola	-15.65000	14.06667	1318	INOVA		GPRS	x	x	x	x	x	x	x	x				x		11.04.2014	undetermined
Ganda	Angola	-12.95000	14.63333	1412	INOVA		GPRS	x	x	x	x	x	x	x	x				x		08.04.2014	undetermined
Gove	Angola	-13.45500	15.85900	1741	Adcon/OTT		GPRS	x		x	x	x		x							18.06.2012	active
Great Welwitschia	Angola	-15.56800	12.14000	98	Adcon/OTT		GPRS	x			x	x				x					26.10.2015	active
Humpata	Angola	-15.06900	13.35100	1880	Adcon/OTT		GPRS	x		x	x	x	x	x							17.10.2014	active
IMA - Huambo	Angola	-12.81500	15.64100	1736	Adcon/OTT		GPRS	x		x	x	x	x	x							01.01.2014	inactive
Iona Coastal	Angola	-16.80562	11.88445	187	Adcon/OTT		MAN	x		x	x	x									15.01.2017	active
ISPKS - Sumbe	Angola	-11.28500	13.89600	275	Adcon/OTT		GPRS	x		x	x	x	x	x							02.02.2016	active
Kessua	Angola	-9.46400	16.28500	1115	Adcon/OTT		GPRS	x		x	x	x	x	x							24.11.2014	active
Kibala (Catofe)	Angola	-10.73597	14.98446	1272	INOVA		GPRS	x	x	x	x	x	x	x	x				x		14.04.2014	undetermined
Matala	Angola	-14.88700	15.08300	1204	Adcon/OTT		GPRS	x		x	x	x	x	x							08.10.2013	active
Muconda	Angola	-10.58769	21.31772	1096	INOVA		GPRS	x	x	x	x	x	x	x	x				x		05.07.2014	undetermined
Mukongo	Angola	-14.74900	12.50500	390	Adcon/OTT		GPRS	x		x	x	x	x	x							26.10.2014	active
Munhino	Angola	-14.95655	12.97733	402	Adcon/OTT		MAN	x		x	x	x	x	x							23.04.2016	active
Namacunde	Angola	-17.31200	15.85300	1112	Adcon/OTT		GPRS	x		x	x	x		x							01.04.2015	inactive
Namibe	Angola	-15.15900	12.17800	11	Adcon/OTT		GPRS	x		x	x	x	x	x		x					30.10.2014	active
Onjiva	Angola	-16.97600	15.61500	1119	Adcon/OTT		GPRS	x		x	x	x		x							01.04.2015	active
PN Bicuar	Angola	-15.10000	14.83330	1243	Adcon/OTT		SAT	x	x	x	x	x	x	x			x				21.03.2015	active
Projecto Terra do Futuro (PTF)	Angola	-10.46700	15.71100	1602	Adcon/OTT		GPRS	x		x	x	x	x	x							03.04.2015	inactive
Quibaxi	Angola	-8.51300	14.59000	872	Adcon/OTT		GPRS	x		x	x	x		x							11.05.2012	active
Tchivinguiro	Angola	-15.16900	13.29900	1662	Adcon/OTT		GPRS	x		x	x	x	x	x							02.04.2015	active
Tundavala	Angola	-14.84500	13.40700	2060	Adcon/OTT		GPRS	x		x	x	x	x	x							18.10.2014	17.04.2016 (2)
Tundavala Observatory	Angola	-14.79990	13.40750	2300	Adcon/OTT		GPRS	x	x	x	x	x	x	x							18.03.2015	active
UJES-Huambo	Angola	-12.86300	15.73100	1664	Adcon/OTT		GPRS	x	x	x	x	x	x	x							02.10.2013	inactive
Wako-Kungo	Angola	-11.41100	15.12900	1331	Adcon/OTT		GPRS	x		x	x	x	x	x							02.06.2012	active
Xangongo	Angola	-16.71900	14.98200	1123	Adcon/OTT		GPRS	x		x	x	x		x							20.05.2015	active
Baines Drift	Botswana	-22.48983	28.69675	709	CTS	68088	SAT	x	x	x	x	x	x	x	x				x	x	17.03.2015	active
Ghanzi	Botswana	-21.71508	21.65317	1137	CTS	68024	GPRS	x	x	x	x	x	x	x	x			x	x	x	13.02.2014	active
Goodhope	Botswana	-25.46025	25.42678	1275	CTS	68325	GPRS	x	x	x	x	x	x	x	x			x	x	x	01.02.2014	active
Lephepe	Botswana	-23.36564	25.84719	1024	CTS	68151	GPRS	x	x	x	x	x	x	x	x			x	x	x	06.02.2014	active
Lotlhakane East	Botswana	-25.08000	25.43000	1216	Cimel		GPRS	x	x	x	x	x	x	x					x		25.08.2015	active
Mababe	Botswana	-19.01800	23.96669	931	CTS	68028	SAT	x	x	x	x	x	x	x	x						30.03.2015	active
Mahalapye	Botswana	-23.11253	26.85922	1015	CTS	68148	GPRS	x	x	x	x	x	x	x	x			x	x	x	07.02.2014	active
Malopowabojang	Botswana	-25.20000	25.57000	1224	Cimel		GPRS	x	x	x	x	x	x	x					x		27.08.2015	active
Mogobane	Botswana	-24.98000	25.70000	1076	Cimel		GPRS	x	x	x	x	x	x	x					x		25.08.2015	active
Ngwatle	Botswana	-23.71239	21.07972	1176	CTS	68218	SAT	x	x	x	x	x	x	x	x				x	x	25.08.2015	active
Pandamatenga	Botswana	-18.54463	25.63583	1074	CTS	68030	GPRS	x	x	x	x	x	x	x	x			x	x	x	21.02.2014	active
Ramotswa	Botswana	-24.88000	25.88000	1040	Cimel		GPRS	x	x	x	x	x	x	x					x		25.08.2015	active
Ranaka	Botswana	-24.90000	25.45000	1224	Cimel		GPRS	x	x	x	x	x	x	x					x		25.08.2015	active
Shakawe	Botswana	-18.36856	21.83931	1002	CTS	68026	GPRS	x	x	x	x	x	x	x	x			x	x	x	12.02.2014	active
Sowa	Botswana	-20.54742	26.07842	911	CTS	68038	GPRS	x	x	x	x	x	x	x	x			x	x	x	22.02.2014	active
Tsabong	Botswana	-26.03136	22.40086	960	CTS	68328	GPRS	x	x	x	x	x	x	x	x			x	x	x	14.02.2014	active
Tshane	Botswana	-24.01928	21.86856	1125	CTS	68226	GPRS	x	x	x	x	x	x	x	x			x	x	x	14.02.2014	active
Tubu (Okavango Delta)	Botswana	-19.35786	22.28400	967	CTS	68027	SAT	x	x	x	x	x	x	x					x	x	26.03.2015	active
Werda	Botswana	-25.26800	23.25919	1030	CTS	68320	GPRS	x	x	x	x	x	x	x	x			x	x	x	07.02.2014	active
Xade	Botswana	-22.34072	23.02983	1004	CTS	68084	SAT	x	x	x	x	x	x	x	x				x	x	22.08.2015	active
Alex Muranda Livestock Devel	Namibia	-18.36430	19.25620	1166	CTS		GPRS	x	x	x	x	x	x	x	x						07.10.2010	active
Aussinanis	Namibia	-23.44354	15.04594	405	Gobabeb		GPRS	x	x	x	x	x		x	x						07.08.2014	active
Bagani	Namibia	-18.09464	21.55997	1008	CTS		GPRS	x	x	x	x	x	x	x	x						19.02.2013	active
Claratal	Namibia	-22.78760	16.81440	1950	CTS		GPRS	x	x	x	x	x	x	x	x						24.11.2010	active
Coastal Met	Namibia	-23.05631	14.62595	94	Gobabeb		GPRS	x	x	x	x	x	x	x	x						07.09.2014	active
Conception Water	Namibia	-24.01533	14.55038	9	Gobabeb		SAT	x	x	x	x	x		x	x						01.01.2017	active
Dieprivier (Namib Desert Lodg	Namibia	-24.12960	15.89470	1056	CTS		GPRS	x	x	x	x	x	x	x	x						07.06.2011	active
Erichsfelde	Namibia	-21.59860	16.90120	1499	CTS		GPRS	x	x	x	x	x	x	x	x						26.11.2010	inactive
Ganab	Namibia	-23.12180	15.53830	1002	CTS		GPRS	x	x	x	x	x	x	x	x	x					09.06.2011	active
Garnet Koppie	Namibia	-23.11539	15.30504	733	Gobabeb		GPRS	x	x	x	x	x	x	x	x						14.08.2014	active
Gellap Ost	Namibia	-26.40110	18.00720	1080	CTS		GPRS	x	x	x	x	x	x	x	x						24.02.2011	active
Giribisvlakte	Namibia	-19.09570	13.32611	630	CTS		SAT	x	x	x	x	x	x	x	x						27.06.2015	active
Gobabeb Met	Namibia	-23.56044	15.04100	406	Gobabeb		GPRS	x	x	x	x	x			x						04.10.2014	active
Hamoye	Namibia	-18.23475	19.73231	1122	MCS		GPRS	x	x	x	x	x	x	x	x			x			18.02.2013	active

Name	Country	Latitude	Longitude	Altitude [m]	Type	WMO	Transmission	Air temperature	Soil temperature	Wind	Rain	Relative humidity	Barometric pressu	Solar irradiance	Leaf wetness	Fog precipitation	Soil moisture	Sunshine duration	Dew point	Wet bulb	First data	Status/Last data
John Pandeni	Namibia	-19.70778	18.03528	1434	MCS		GPRS	x	x	x	x	x	x	x	x			x			24.11.2012	active
Kalahari	Namibia	-24.16283	18.47672	1229	MCS		GPRS	x	x	x	x	x	x	x	x			x			12.10.2012	inactive
Kalimbeza	Namibia	-17.54472	24.52669	939	CTS		GPRS	x	x	x	x	x	x	x	x						17.07.2013	active
Kanovlei	Namibia	-19.33269	19.48108	1217	CTS		SAT	x	x	x	x	x	x	x	x						12.02.2016	active
Kaoko Otavi	Namibia	-18.30023	13.65983	1427	CTS		SAT	x	x	x	x	x	x	x	x						17.04.2016	active
Karios (Gondwana Canyon Lod	Namibia	-27.67450	17.81950	893	CTS		GPRS	x	x	x	x	x	x	x	x						23.02.2011	active
Khorixas	Namibia	-20.37892	14.96952	967	CTS		SAT	x	x	x	x	x	x	x	x						27.02.2016	active
Kleinberg	Namibia	-22.98950	14.72817	185	MCS		GPRS	x	x	x	x	x	x	x	x			x			24.03.2011	active
Kleinberg-FN	Namibia	-22.98928	14.72793	184	Gobabeb		GPRS	x	x	x	x	x		x	x						07.08.2014	active
Koichab Pan	Namibia	-26.20761	15.86300	525	CTS		SAT	x	x	x	x	x	x	x	x						19.10.2015	active
Konop Pos	Namibia	-20.16800	14.96456	1073	CTS		SAT	x	x	x	x	x	x	x	x						29.11.2016	active
Mahenene	Namibia	-17.44433	14.78481	1114	MCS		GPRS	x	x	x	x	x	x	x	x			x			24.02.2012	active
Mannheim	Namibia	-19.16861	17.76336	1222	MCS		GPRS	x	x	x	x	x	x	x	x			x			06.12.2012	active
Marble Koppie	Namibia	-22.96948	14.98968	421	Gobabeb		GPRS	x	x	x	x	x		x	x						07.08.2014	active
Marienflusstal	Namibia	-17.60886	12.60181	572	CTS		SAT	x	x	x	x	x	x	x	x						30.06.2015	07.05.2017 (1)
Mashare	Namibia	-17.89460	20.20850	1066	CTS		GPRS	x	x	x	x	x	x	x	x						17.02.2012	inactive
Mopanie Pos 6	Namibia	-20.25674	15.06718	1097	CTS		SAT	x	x	x	x	x	x	x	x						26.11.2016	active
Narais - Duruchaus	Namibia	-23.12125	16.90061	1627	CTS		GPRS	x	x	x	x	x	x	x	x						25.11.2010	active
Ngoma	Namibia	-17.89950	24.70794	938	CTS		GPRS	x	x	x	x	x	x	x	x						16.07.2013	inactive
Nico	Namibia	-25.31275	17.83458	1058	MCS		GPRS	x	x	x	x	x	x	x	x			x			02.04.2010	active
Ogongo	Namibia	-17.67853	15.29481	1111	CTS		GPRS	x	x	x	x	x	x	x	x						25.02.2012	active
Okahandja (NRFC)	Namibia	-22.00564	16.91797	1321	CTS		GPRS	x	x	x	x	x	x	x	x						23.08.2012	active
Okamboro	Namibia	-22.00949	17.04139	1461	MCS		GPRS	x	x	x	x	x	x	x	x			x			24.03.2011	active
Okangwati	Namibia	-17.43025	13.27810	1081	CTS		SAT	x	x	x	x	x	x	x	x						15.04.2016	active
Okapya	Namibia	-18.47250	17.33908	1138	CTS		GPRS	x	x	x	x	x	x	x	x						24.02.2012	active
Okashana	Namibia	-18.41111	16.63853	1106	MCS		GPRS	x	x	x	x	x	x	x	x			x			25.02.2012	active
Okomumbonde	Namibia	-20.48327	17.34317	1389	MCS		GPRS	x	x	x	x	x	x	x	x			x			21.11.2012	active
Omatako Ranch	Namibia	-21.50940	16.72910	1496	CTS		GPRS	x	x	x	x	x	x	x	x						08.12.2010	active
Omatjenne	Namibia	-20.44278	16.49333	1376	MCS		GPRS	x	x	x	x	x	x	x	x			x			03.02.2012	active
Oshaambelo	Namibia	-17.84286	14.77008	1114	MCS		GPRS	x	x	x	x	x	x	x	x			x			24.02.2012	active
Rooisand	Namibia	-23.29453	16.11467	1176	MCS		GPRS	x	x	x	x	x	x	x	x			x			24.03.2011	active
Sachinga	Namibia	-17.67367	24.03189	982	CTS		GPRS	x	x	x	x	x	x	x	x						17.07.2013	active
Salt Works	Namibia	-23.02352	14.46317	5	Gobabeb		GPRS	x	x	x	x	x		x	x						20.11.2017	active
Sandveld	Namibia	-22.04450	19.13210	1527	CTS		GPRS	x	x	x	x	x	x	x	x						11.01.2011	active
Sonop Research Station	Namibia	-19.01010	18.90390	1218	CTS		GPRS	x	x	x	x	x	x	x	x						09.10.2010	inactive
Sophies Hoogte	Namibia	-23.00681	14.89087	334	Gobabeb		GPRS	x	x	x	x	x		x	x						07.08.2014	active
Station 8	Namibia	-23.26530	15.05627	487	Gobabeb		GPRS	x	x	x	x	x		x	x						07.08.2014	active
Tsumis	Namibia	-23.72978	17.19386	1376	MCS		GPRS	x	x	x	x	x	x	x	x			x			25.05.2012	active
Tsumkwe Breeding Station	Namibia	-19.61560	20.44200	1153	CTS		GPRS	x	x	x	x	x	x	x	x						05.08.2011	active
Vogelfederberg	Namibia	-23.09797	15.02903	501	Gobabeb		GPRS	x	x	x	x	x	x	x	x						11.08.2014	active
Waterberg	Namibia	-20.39710	17.35290	1575	CTS		GPRS	x	x	x	x	x	x	x	x						09.09.2011	active
Windhoek (NBRI)	Namibia	-22.57070	17.09570	1700	CTS		GPRS	x	x	x	x	x	x	x	x						01.10.2010	active
Windhoek (Satellite)	Namibia	-22.57238	17.09481	1737	CTS		SAT	x	x	x	x	x	x	x	x						09.07.2014	active
Wlotzkasbaken	Namibia	-22.31490	14.46210	55	CTS		GPRS	x	x	x	x	x	x	x	x	x					10.06.2011	active
Alexanderbay Lichen Field	South Africa	-28.62496	16.50674	80	Adcon/OTT		GPRS	x		x	x	x				x					01.10.2015	active
Alpha	South Africa	-26.76178	20.62504	872	Adcon/OTT		GPRS	x	x	x	x	x	x	x							03.10.2015	active
Eksteenfontein	South Africa	-28.83653	17.29039	606	Adcon/OTT		GPRS	x	x	x	x	x	x	x							05.10.2015	active
Koeroegabvlakte	South Africa	-28.23590	17.02557	641	Adcon/OTT		SAT	x	x	x	x	x	x	x			x				08.03.2015	active
Moedverloor	South Africa	-31.47273	18.44542	147	Adcon/OTT		GPRS	x	x	x	x	x	x	x		x					06.10.2016	active
Numees	South Africa	-28.31426	16.96585	391	Adcon/OTT		SAT	x	x	x	x	x	x	x		x	x				06.03.2015	active
Paulshoek	South Africa	-30.39500	18.28118	996	Adcon/OTT		SAT	x	x	x	x	x	x	x			x				11.10.2015	active
Ratelgat	South Africa	-31.28616	18.60281	209	Adcon/OTT		GPRS	x	x	x	x	x	x	x		x					10.10.2015	inactive
Soebatsfontein	South Africa	-30.18294	17.55062	244	Adcon/OTT		SAT	x	x	x	x	x	x	x			x				11.10.2015	active
Vandersterrberg	South Africa	-28.47126	17.11159	1063	Adcon/OTT		GPRS	x	x	x	x	x	x	x		x					07.03.2015	active
Verlorenvlei	South Africa	-32.59810	18.68285	53	Adcon/OTT		GPRS	x	x	x	x	x	x	x							24.09.2015	active
Yellow Dune - Grootderm	South Africa	-28.61105	16.65436	161	Adcon/OTT		GPRS	x	x	x	x	x	x	x		x					09.03.2015	active
Chadiza	Zambia	-14.06000	32.43200	1056	Adcon/OTT		GPRS	x	x	x	x	x	x	x							29.06.2015	active
Copperbelt University	Zambia	-12.80610	28.23740	1220	Adcon/OTT		GPRS	x	x	x	x	x	x	x							10.04.2015	active
Dongwe	Zambia	-14.01259	24.02188	1071	Adcon/OTT		SAT	x	x	x	x	x	x	x			x				14.05.2015	inactive
Kabwe Mulungushi	Zambia	-14.29257	28.56632	1142	Adcon/OTT		GPRS	x	x	x	x	x	x	x							08.10.2013	active
Kafue National Park-Tatayoyo	Zambia	-14.90153	24.43200	1231	Adcon/OTT		GPRS	x	x	x	x	x	x	x							06.04.2015	inactive
Kalabo	Zambia	-14.98895	22.68175	1018	Adcon/OTT	67625	GPRS	x	x	x	x	x	x	x							02.12.2013	active
Kalomo	Zambia	-16.96000	26.47500	1274	Adcon/OTT		GPRS	x	x	x	x	x	x	x							24.02.2015	inactive
Kasempa	Zambia	-13.45696	25.83370	1227	Adcon/OTT	67541	GPRS	x	x	x	x	x	x	x							26.11.2013	active
Luampa	Zambia	-15.14233	24.49237	1130	Adcon/OTT		GPRS	x	x	x	x	x	x	x							05.04.2015	inactive
Lusaka Int. Airport	Zambia	-15.31929	28.44050	1149	Adcon/OTT	67665	GPRS	x	x	x	x	x	x	x							08.10.2013	active
Lusaka University of Zambia	Zambia	-15.39117	28.33204	1260	Adcon/OTT		GPRS	x	x	x	x	x	x	x							10.10.2013	active
Mpulungu	Zambia	-8.77300	31.11700	801	Adcon/OTT		GPRS	x	x	x	x	x	x	x							20.05.2015	active
Mwinilunga	Zambia	-11.73998	24.43100	1360	Adcon/OTT	67441	GPRS	x	x	x	x	x	x	x							04.12.2013	active
Namwala	Zambia	-15.75000	26.43300	998	Adcon/OTT		GPRS	x	x	x	x	x	x	x							22.02.2015	active
Nangweshi	Zambia	-16.24592	23.23711	1014	Adcon/OTT		GPRS	x	x	x	x	x	x	x							23.02.2015	inactive
Samfya	Zambia	-11.37119	29.56057	1194	Adcon/OTT	67469	GPRS	x	x	x	x	x	x	x							06.10.2013	active
Serenje	Zambia	-13.22670	30.21508	1395	Adcon/OTT	67571	GPRS	x	x	x	x	x	x	x							07.10.2013	active
Sesheke	Zambia	-17.47110	24.30130	944	Adcon/OTT	67741	GPRS	x	x	x	x	x	x	x							22.11.2013	active
Zambezi	Zambia	-13.53365	23.10790	1066	Adcon/OTT	67531	GPRS	x	x	x	x	x	x	x							27.11.2013	active

(1) lost by vandalism	GPRS	Transmission via GPRS
(2) shifted to Munhino	SAT	Transmission via satellite
	MAN	Manual download
	active	station measures data
	-	Time series terminated
	inactive	Data flow stopped, maintenance is needed
	undetermined	Status about the station is undetermined

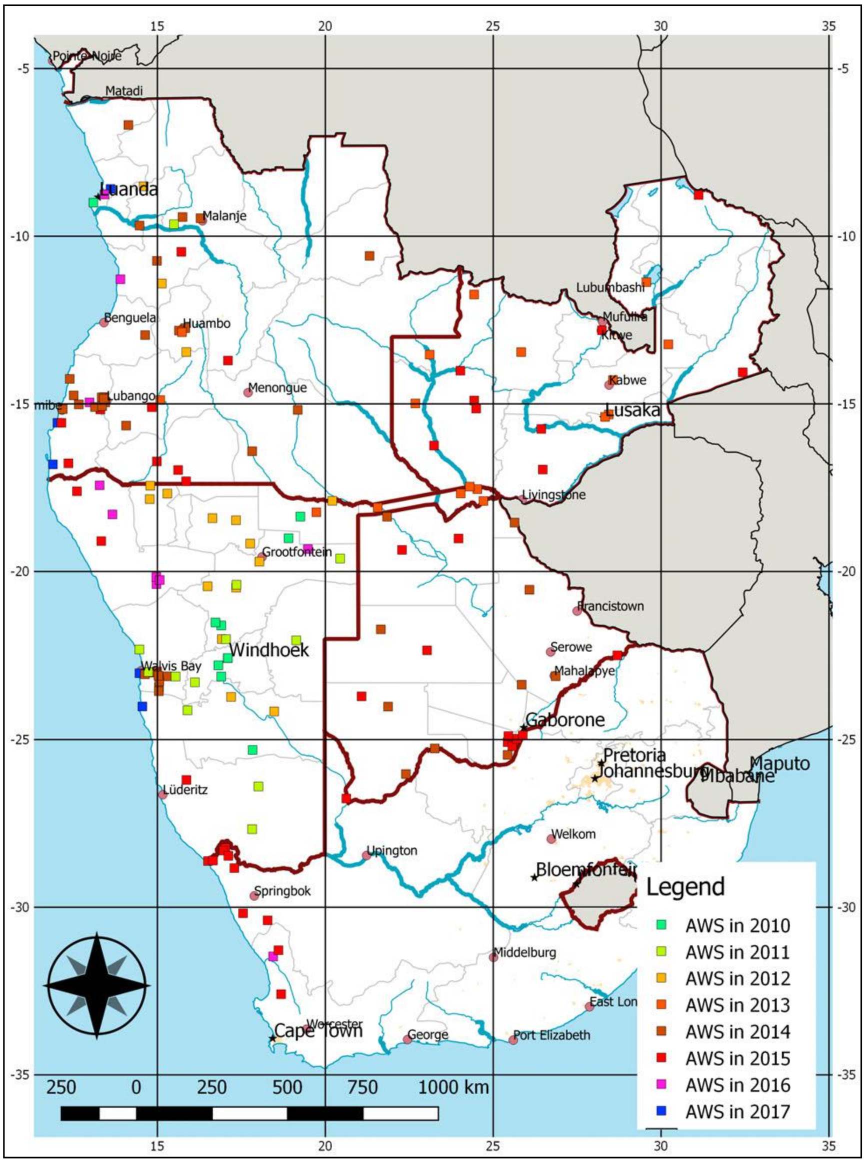

Figure 2: Locations of automatic weather stations within the SASSCAL WeatherNet.

by other sources (see the section 'History'). Each AWS is equipped with several sensors measuring more than ten climatic elements (see Fig. 3, Tab. 3).

Table 2: Number of weather stations within the SASSCAL region and their methods of data transmission

	#	GPRS	SAT	MAN	a	-	i	x
Angola	45	40	2	3	28	3	6	8
Botswana	20	15	5	0	20	0	0	0
Namibia	58	47	11	0	52	1	5	0
South Africa	12	8	4	0	11	0	1	0
Zambia	19	18	1	0	14	0	5	0
Total	154	128	23	3	125	4	17	8

#	Number of weather stations/time series
GPRS	Transmission via GPRS
SAT	Transmission via satellite (Meteosat)
MAN	Manual download
a	Active: data available
-	Time series terminated
i	Inactive: data flow stopped
x	Undetermined

In Table 1, details about the availability of time series for each station are presented, including the first date and, in the case of termination, the last date. Not all stations produced continuous data; causes of data flow interruption include vandalism, communication interruptions, and in some cases the necessity to change the location of certain stations.

The AWSs have been purchased from different providers, coming with a variety of data loggers and sensors (Tab. 4). The variety of types is one of the reasons for the need for careful data management, which has to harmonize the many variants of incoming data.

Table 1 also provides information about locations of AWSs registered by the WMO, and Table 5 compares SASSCAL AWSs with WMO-registered AWSs in the SASSCAL region.

Data transfer

Starting from the respective climate station, the data is transferred over different transmission channels to the FTP server (see Fig. 4 for a simplified representation). From here the raw data are picked up, processed, and written into the database. Several data quality examinations take place during the processing phase (see 'Data processing and quality control'). With the diversity of AWSs, the variety of transfer methods has increased. The providers Adcon/OTT, MCS, and Cimel collect the data first and forward these to the SASSCAL FTP server. The data from most of the Gobabeb AWSs are downloaded remotely from the data logger with the assistance of the Campbell LoggerNet tool. For the AWSs with transmission via Meteosat satellite, an Eumetsat download portal is in use. From there, the current data are retrieved, processed, and forwarded to the SASSCAL FTP server every hour.

The volume of data increases every day: 95 AWSs have a resolution of one record per hour and 69 AWSs have a resolution of four records per hour, which results in 8,904 expected records per day. Despite data loss caused by malfunctions, especially as a result of transmission problems either at the AWS or on the side of the GPRS service provider, on average 7,500 records per day are recorded.

Table 3: Number of stations measuring respective weather variables

	Air temperature	Soil temperature	Wind	Rain	Relative humidity	Barometric pressure	Solar irradiation	Leaf wetness	Fog precipitation	Soil moisture	Sunshine duration	Dew point	Wet bulb
Angola	44	15	42	44	44	32	41	8	4	2	0	8	0
Botswana	20	20	20	20	20	20	20	14	0	0	10	19	14
Namibia	58	58	58	58	58	50	57	58	2	0	14	0	0
South Africa	12	11	12	12	12	11	11	0	6	4	0	0	0
Zambia	19	19	19	19	19	19	19	0	0	1	0	0	0
Total	153	123	151	153	153	132	148	80	12	7	24	27	14

Weather variable
Air temperature (avg, max, min)
Soil temperature
Precipitation / Rain
Wind speed (avg, max, min)
Wind direction
Relative humidity
Barometric pressure
Solar irradiance
Fog precipitation
Leaf wetness

AWS Wlotzkasbaken, 22°18‘54“ S , 14°27‘44“ E

Figure 3: Typical weather variables recorded by the SASSCAL weather stations.

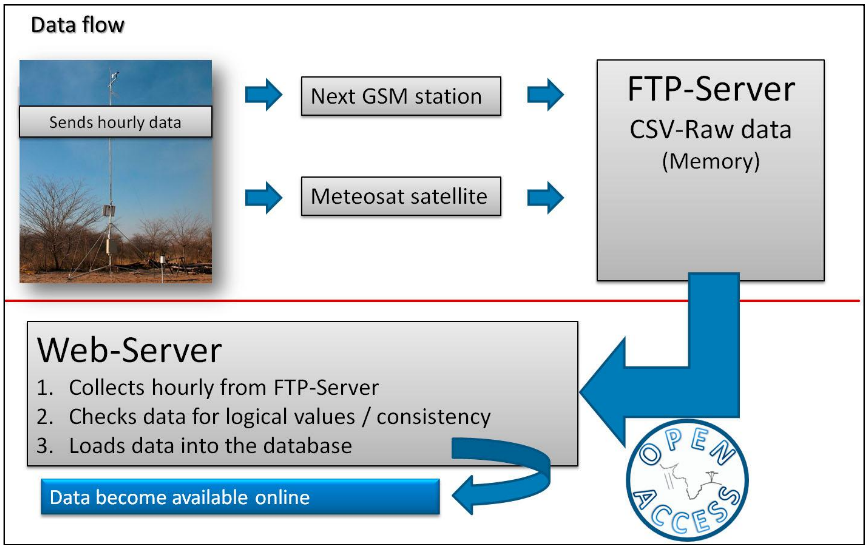

Figure 4: Data flow from the automatic weather station to online presentation.

Table 4: Number of stations per type, **#** number of AWSs, **Adcon** Telemetry / OTT Hydromet Group (Austria/Germany) (own devices), **CTS** Central Technical Supplies (Pty.) Ltd (Namibia) (Campbell, Young, Vaisala), **MCS** Mike Cotton Systems (South Africa) (own devices, Vaisala), **INOVA** (Angola), **Gobabeb** FogNet (Namibia) (Campbell, Young, Vaisala, Setra), **Cimel** Electronique (France)

	#	Adcon	CTS	MCS	INOVA	Gobabeb	Cimel
Angola	45	36	0	0	9	0	0
Botswana	20	0	15	0	0	0	5
Namibia	58	0	33	14	0	11	0
South Africa	12	12	0	0	0	0	0
Zambia	19	19	0	0	0	0	0
Total	154	67	48	14	9	11	5

Data processing and quality control

To provide high-quality data, there are certain prerequisites that need to be met:

1. *Up-to-date, high-quality technical equipment*: sensors, data loggers, and transmitters.
2. *Protected sites*: stations are fenced in or in secure areas such as at police stations or farms.
3. *Support at the station location*: someone from the local village/station is able to undertake minor repairs and maintenance and/or provide security.
4. *Immediate checks on receipt of values for presence and plausibility*: quality checks of data should be carried out by one or two persons per country to assist the IT team in delivering high-quality data and to know in time when one of the sensors has been damaged or stops functioning.
5. *Regular maintenance measures*: regular maintenance is carried out twice annually, but for stations in exposed areas every three months to prevent the formation of rust and blockages of gauges by fine silt (dust) or other debris.
6. *Technical competence in the SASSCAL region*: the lack of manpower to assist in troubleshooting has made it necessary to compile manuals that can be used to train technicians and managers (e.g. Strohbach, 2014).
7. *Stocks with spare parts available within the countries*: spare parts at hand make it possible to effect timely repairs.
8. *Near real-time publication of the data*: not only for general use, but also for the timely detection of problems.
9. *Lean information chains to initiate repairs*: short communication paths considerably accelerate measures in case of malfunctions.

Although these prerequisites are carefully considered within the SASSCAL network, every incoming value must be checked for its reliability and suspicious measured values need to be excluded. In principle, there are several ways to check incoming values for consistency and plausibility (WMO, 2011, 2012).

1. The values must be between acceptable range limits (e.g., barometric pressure depends on altitude).

Climate

2. A value must fit within a known context (e.g., frost in the early afternoon is possible only during the winter season).
3. Logical relationships of values of different parameters must be respected (e.g., the wind speed *minimum* must be less than wind speed *average*, which in turn is to be less than wind speed *maximum*).
4. Consecutive values in a time series must be coherent (e.g., if several consecutive wind speed values are identical, this is an indication of a sensor failure; also, extraordinary rapid changes in specific values indicate sensor failures).
5. The trend of a parameter value must match the trend of other parameter values (e.g., as a rule of thumb, air humidity and leaf wetness values increase when it starts raining).
6. Long-term trends must be consistent (e.g., a rising mean humidity value over more than a year indicates a need for calibration of the humidity sensor).

Items 1, 2, and 3 relate to a single value or combination of values of the same data record and can be checked immediately after arrival of the record. In the case of items 4, 5, and 6, an examination can be carried out only at a later point in time, as data records must be compared with several, possibly even very many, other records.

It has been found to be advantageous to relate interval limits (see point 1 above) to the individual station. This makes it possible to adapt the limits to the local conditions and to detect outliers easier and more precisely. It has also proved useful to adjust the tests to the time of day or season to detect anomalies such as false positive precipitation values in a known dry period (see, e.g., Fig. 5 and Tab. 6). All abnormalities are logged in a database.

Figure 6 shows plausibility checks of the SASSCAL WeatherNet, which are automatically performed when a set of values is received.

Data presentation

For the use of the data from the SASSCAL WeatherNet, data completeness and high data quality are necessary conditions. However, data presentation is equally important. Potential data users must become aware of the network and be informed of the quality and the prerequisites for data availability. The link between on-site measurement and the use of data for scientific or other applications is data processing using the Internet, user-friendly online databases, web presence, and tools of modern data management. This is achieved with the SASSCAL WeatherNet website (www.sasscalweathernet.org), which reveals the obtained data to both the SASSCAL scientific community and any other person interested in weather data.

The website provides information about the characteristics of each AWS

Table 5: Comparison of WMO-registered stations versus stations within SASSCAL WeatherNet

Country	SASSCAL	WMO	both
Angola	45	32	0
Botswana	20	33	14
Namibia	58	20	0
South Africa	12	205	0
Zambia	19	37	8
Total	154	327	22

Sources:

Column *SASSCAL*: AWSs within SASSCAL WeatherNet
Column *WMO*: Registered weather stations at WMO; see https://oscar.wmo.int/surface//index.html#/search/station#stationSearchResults
Column *both*: Intersection of AWSs listed both in column *SASSCAL* and column *WMO, for example: 14 of the 20 Botswana SASSCAL AWSs are among the 33 Botswana WMO-registered AWSs*

Table 6: Registered causes of system failures

Causes of system failures
Vandalism, whole station got lost, or solar panels and batteries were stolen
Rain gauges indicate false precipitation, caused by, for example, small animals (wasps, baby gecko)
Insects building their nests around air temperature/humidity sensors
Formation of rust and blockages of gauges because of fine silt (dust) and debris such as leaves
Sensors get damaged by livestock and wild animals (donkeys, horses, cattle, rodents, and ants) chewing off cables and sensors
Network failures; antenna cables disconnected or damaged; cell phone modems malfunctions

Figure 5:
Wasps inside the sensor causing false rainfall values at Kalimbeza weather station.

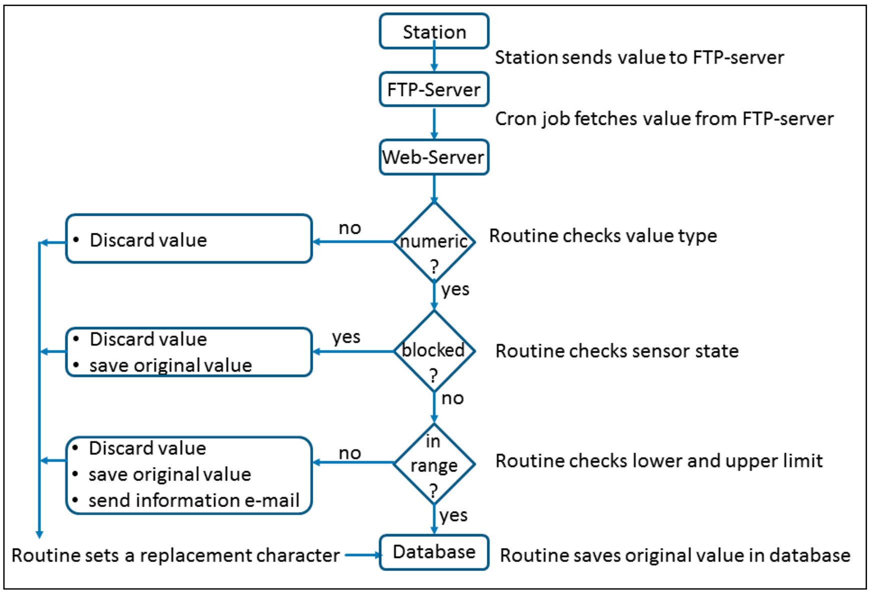

Figure 6: Flow diagram of data plausibility checks as part of data quality control procedures.

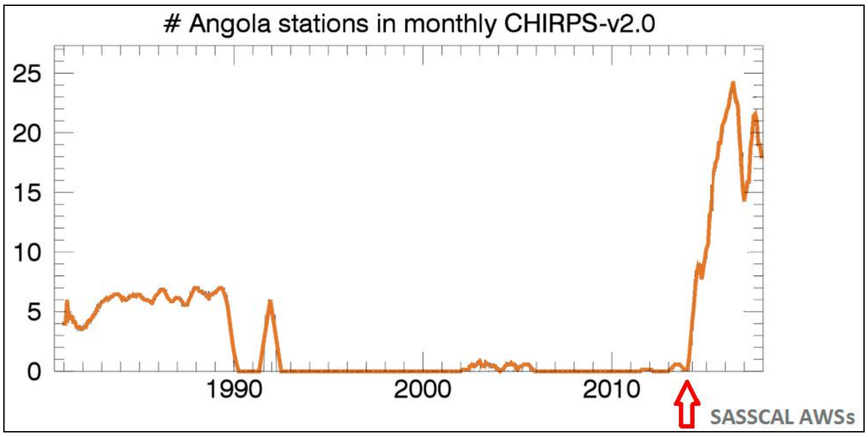

Figure 7: Number of weather stations in Angola in the monthly CHIRPS-v2.0, Climate Hazards Group Infrared Precipitation with Stations, ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRPS-2.0/diagnostics/stations-perMonth-byCountry/pngs/Angola.002.station.count.CHIRPS-v2.0.png (last access February 2018).

and allows users to inspect the current data in different temporal resolutions, from hourly values (or quarter-hourly, depending on the sensor) to daily and monthly averages. The data are visualized in the form of tables and intuitive diagrams. Small data packages can be downloaded by the user without restrictions. Bulk data are supplied on request.

The popularity of this data source is illustrated by the following web statistics (monthly figures for December 2017): 946,750 hits; 691,917 pages; 65,844,870 kB download; 5,230 different IP addresses ≈ visitors.

A special service is provided as a morning email: every day at 7:30 a.m. (GMT+2), an automated routine sends an email to a circle of currently 100 subscribers with the parameters of the previous day's rainfall and average, maximum, and minimum temperatures.

System architecture

The SASSCAL IT Team at the University of Hamburg uses a rented LINUX virtual server with Ubuntu OS 14.04 LTS 64bit + Plesk v12.5.30, memory 32 GB, storage 800 GB. The data are stored in a MySQL database and comprise more than 10 million rows in the tables with the finest (hourly or quarter-hourly) resolution. All the different routines and webpages are programmed with PHP.

Data applications and usage policy

The data were initially intended as a basis to understand changes in the environment resulting from the expected climate change in the following SASSCAL thematic areas: climate, water, agriculture, forestry, and biodiversity. Scientists in the SASSCAL consortium and collaborating researchers have used the time series extensively for both climatic research (e.g., Eiselt et al., 2017; Funk et al., 2015; Meyer et al., 2017; Siepker & Harms, 2017) and biological/ecological work (e.g., Strohbach & Kutuahuripa, 2014; Campbell et al., 2015; van Holsbeeck et al., 2016; Navarro et al., 2016; Scherer et al., 2016; Strohbach, 2017; Beyer et al., 2018). Another SASSCAL project supported the national meteorological services to improve the integration of data into their climate databases and internal processes (see Posada et al., 2016, 2018). In the meantime, data requests to SASSCAL are not only for the abovementioned topics but also from many other groups, which use the data for a variety of purposes such as road and infrastructure planning, wind and solar energy projects, fire management systems, and cooperation with other weather networks (e.g., Kenabatho et al., 2018; Kumwenda et al., 2017; Siepker & Harms, 2017). Additionally, data from the SASSCAL WeatherNet have been used in the creation of precipitation maps by CHIRPS since 2015 (Climate Hazards Group Infrared Precipitation with Stations; Funk et al., 2015). These are used in agroclimatology and food security monitoring systems such as FEWS-NET (Famine Early Warning Systems Network; Brown et al., 2007) and FLDAS (FEWS NET Land Data Assimilation Systems; McNally et al., 2017).

SASSCAL has a data usage policy that makes it easy for a data user to receive the data: 'Free use of the data is granted for non-commercial and educational purposes. Commercial use can be granted based on request to SASSCAL.' The most important condition is a citation of SASSCAL as data source: 'For any use SASSCAL has to be acknowledged as "SASSCAL WeatherNet (2017), www.sasscalweathernet.org"', as stated in the

Climate

website section disclaimer. Commercial use of the data is not desired. The low inhibition threshold for sharing of the data and the discernible potential for use is a challenge for the team of the SASSCAL WeatherNet: the delivery of quality-tested data as file batches is fundamentally different from the continuous feeding of data into foreign systems and presents an additional burden to the data management team. If such commitments of data supply are made, conditions must be created for a continuous flow of data from the stations to the collecting server, quality assurance of the data close to the time of measurement, and postdelivery options for late-arriving data and updates. For these tasks, the organizational framework must be in place and the technology must be optimized. A necessary technical precondition is the establishment of data quality check routines (see 'Data processing and quality control').

Conclusions and outlook

At the end of the seven years of implementation, the question may be asked whether the abovementioned effort has been a worthwhile investment of resources. We come to an affirmative answer and regard the following points as crucial aspects:

1. There is no doubt that climate change is one of the major drivers of environmental and societal change (IPCC, 2015). Therefore, it is essential to provide robust measurements that inform on the direction and intensity of change.
2. In large areas of the SASSCAL region (more so in the northern than in the southern parts), the coverage of operating AWSs in 2010 was below one station per 100,000 km². This was a very poor overall spatial coverage compared to the geographical diversity within the SASSCAL region (Helmschrot et al., 2015; Kaspar et al., 2015). Except for in South Africa, which has a dense weather observation network, the majority of the stations in the other SASSCAL countries were located at major airports and cities while vast areas that are highly relevant for the formation of important meteorological processes were not covered. Studies in Sudan (70 stations, area ≈ 2.5 million km²) and Nigeria (28 stations, area ≈ 1 million km²) indicate station densities of 1 per 35,000 km² (Omer, 2008; Fadare 2010). Today SASSCAL operates an AWS network at a density of more than 60 stations per 1 million km² in its core areas. This figure is still low compared to industrialized countries, but it covers the spatial diversity of the SASSCAL region far better than ever before (see Fig. 7 with the number of Angolan weather stations used by CHIRPS, showing the increase in AWS numbers after a long period of civil war without data availability). The improved network is highly appreciated by climate researchers, who use the improved data for modelling, and by weather services, which integrate the new data into their forecasting.
3. With the observation network in place, allowing the capture of climate variability and supporting climate change assessments, researchers are now able to integrate field observations, environmental modelling, and measured biotic and social data with reliable and high-resolution climate data.
4. Although it was possible to apply for and obtain weather data from the national weather services in the past, the new open-access standard, jointly developed with the national weather services, allows easy and fast downloading of all data by every researcher and decision-maker. SASSCAL received a large number of letters that expressed appreciation for this improved access to urgently needed weather data in times of rapid climate change.
5. The openly accessible weather data of the SASSCAL WeatherNet allowed a wide availability of the most recent weather data and, therefore, an increased awareness of weather and climate change by the wider public. A striking example is regular rainfall reports in various print and radio media in Namibia based on SASSCAL WeatherNet data. The importance of these public-domain data has repeatedly been highlighted in statements made by many politicians.

In summary, we conclude that it was a very good investment by SASSCAL to set up the SASSCAL WeatherNet.

For the time ahead, it is particularly important to ensure that the measures taken in the years to come are sustainable and that moderate growth is achieved. The WeatherNet workshop 2017 (see 'History') emphasized the importance of AWS maintenance and capacity building with training in data management, archiving, data exchange, implementation of software, web development, satellite communication, and international data exchange.

To guarantee long-term data availability, the anchoring of knowledge in the SASSCAL region is important beyond the funding period of the SASSCAL project. The SASSCAL Open Access Data Centre (OADC) intends to take over the tasks of data management and online presentation, and the national meteorological services are ready to continue the maintenance of the AWSs handed over by SASSCAL.

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References

Beyer, M., Gaj, M., Königer, P., Hamutoko, J.T., Wanke, H., Wallner, M. & Himmelsbach, T. (2018). Isotopenhydrologische Methoden (^{2}H, ^{18}O) zur Bestimmung der Grundwasserneubildung in Trockengebieten: Potenzial und Grenzen. *Grundwasser*, **23**, 731–90.

Brown, M.E., Funk, C.C., Galu, G. & Choularton, R. (2007) Earlier famine warning possible using remote sensing and models. *EOS, Transactions, American Geophysical Union*, **88**, 381–382.

Campbell, H., Fellowes, M.D. & Cook, J.M. (2015) Species diversity and dominance-richness relationships for ground and arboreal ant (Hymenoptera: Formicidae) assemblages in Namibian desert, saltpan, and savannah. *Myrmecological News*, **21**, 37–47.

Eiselt, K.U., Kaspar, F., Mölg, T., Krähenmann, S., Posada, R. & Riede, J.O. (2017) Evaluation of gridding procedures for air temperature over southern Africa. *Advances in Science and Research*, **14**, 163–173.

Fadare, D.A. (2010) The application of artificial neural networks to mapping of wind speed profile for energy application in Nigeria. *Applied Energy*, **87**, 934–942.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A. & Michaelsen, J. (2015) The climate hazards infrared precipitation with stations — a new environmental record for monitoring extremes. *Scientific Data*, **2**, article 150066.

Helmschrot, J., Muche, G., Hillmann, T., Kanyanga, J., Butale, M., Nascimento, D., Kruger, S., Strohbach, B., Seely, M., Ribeiro, C., De Clercq, W., Kenabatho, P., Josenhans, K., & Jürgens, N. (2015) SASSCAL WeatherNet to support regional weather monitoring and climate-related research in Southern Africa. *Proceedings of the International Association of Hydrological Sciences*, **366**, 170–171.

IPCC (2015) *Climate change 2014 – synthesis report*. http://www.ipcc.ch/report/ar5/syr/

Jürgens, N., Haarmeyer, D.H., Luther-Mosebach, J., Dengler, J., Finckh, M. & Schmiedel, U. (2010) *Biodiversity in southern Africa 1: patterns at local scale — the BIOTA Observatories*. Klaus Hess Publishers, Göttingen & Windhoek.

Kaspar, F., Helmschrot, J., Mhanda, A. et al. (2015) The SASSCAL contribution to climate observation, climate data management and data rescue in Southern Africa. *Advances in Science and Research*, **12**, 171–177.

Kenabatho, P.K., Parida, B.P. & Matlhodi, B. (2018) Linking scientific research to development agenda: the case of a hydrometeorological project in the Notwane catchment, Botswana. *Handbook of Research on Geospatial Science and Technologies*, pp. 374–391. IGI Global, Hershey.

Kumwenda, B., Mwaku, W., Mulongoti, D. & Louie, H. (2017) Integration of solar energy into the Zambia power grid considering ramp rate constraints. *2017 IEEE PES-IAS PowerAfrica Conference Proceedings*, 254–259.

McNally, A., Arsenault, K., Kumar, S., Shukla, S. Peterson, P., Wang, S., Funk, C., Peters-Lidard, C.D. & Verdin, J.P. (2017) A land data assimilation system for sub-Saharan Africa food and water security applications. *Scientific Data*, **4**, article 170012.

Meyer, H., Drönner, J. & Nauss, T. (2017) Satellite-based high-resolution mapping of rainfall over southern Africa. *Atmospheric Measurement Techniques*, **10**, 2009–2019.

Navarro, A., Rolim, J., Miguel, I., Catalão, J., Silva, J., Painho, M. & Vekerdy, Z. (2016) Crop monitoring based on SPOT-5, Take-5, and Sentinel-1A data for the estimation of crop water requirements. *Remote Sensing*, **8**, 525.

Omer, A.M. (2008) On the wind energy resources of Sudan. *Renewable and Sustainable Energy Reviews*, **12**, 2117–2139.

Posada, R., Nascimento, D., Neto, F.O.S., Riede, J. & Kaspar, F. (2016) Improving the climate data management in the meteorological service of Angola: experience from SASSCAL. *Advances in Science and Research*. **13**, 97–105.

Posada, R., Riede. J., Kaspar, F., Mhanda, A., Radithupa, M., Stegling, J., Nascimento, D., Tima, L., Nkonde, E., Swaswa, M. & Waitolo, D. (2018) Cooperation of meteorological services within SASSCAL on improving the management of observed climate data. This volume.

Scherer, C., Jeltsch, F., Grimm, V. & Blaum, N. (2016) Merging trait-based and individual-based modelling: An animal functional type approach to explore the responses of birds to climatic and land use changes in semi-arid African savannas. *Ecological Modelling*, **326**, 75–89.

Siepker, E.B.J. & Harms, T.M. (2017) On the potential value of interval-deficient wind data. *Journal of Wind Engineering and Industrial Aerodynamics,* **165**, 100–114.

Strohbach, B.J. (2014) *The SASSCAL / MAWF Weather Stations Network in Namibia. Overview of equipment and data transfer*. Polytechnic of Namibia, Windhoek.

Strohbach, B.J. (2017) Vegetation of the Auas-Oanob Conservancy in the Khomas Hochland of Namibia. *Namibian Journal of Environment*, **1**, 14–33.

Strohbach, B.J. & Kutuahuripa, J.T. (2014) Vegetation of the Eastern Communal Conservancies in Namibia: II. Environmental drivers. *Koedoe — African Protected Area Conservation and Science*, **56**, 1–12.

Van Holsbeeck, S., De Cauwer, V., De Ridder, M., Fichtler, E., Beeckman, H. & Mertens, J. (2016) Annual diameter growth of *Pterocarpus angolensis* (Kiaat) and other woodland species in Namibia. *Forest Ecology and Management*, **373**, 1–8.

World Meteorological Organization (2011) *WMO guide to climatological practices*. WMO-No. 100. World Meteorological Organization, Geneva.

World Meteorological Organization (2012) *WMO guide to THE Global Observing System*. WMO-No. 488. World Meteorological Organization, Geneva.

References [CrossRef]

Beyer, M., Gaj, M., Königer, P., Hamutoko, J.T., Wanke, H., Wallner, M. & Himmelsbach, T. (2018). Isotopenhydrologische Methoden (^{2}H, ^{18}O) zur Bestimmung der Grundwasserneubildung in Trockengebieten: Potenzial und Grenzen. *Grundwasser*, **23**, 731–90. CrossRef

Brown, M.E., Funk, C.C., Galu, G. & Choularton, R. (2007) Earlier famine warning possible using remote sensing and models. *EOS, Transactions, American Geophysical Union*, **88**, 381–382. CrossRef

Campbell, H., Fellowes, M.D. & Cook, J.M. (2015) Species diversity and dominance-richness relationships for ground and arboreal ant (Hymenoptera: Formicidae) assemblages in Namibian desert, saltpan, and savannah. *Myrmecological News*, **21**, 37–47.

Eiselt, K.U., Kaspar, F., Mölg, T., Krähenmann, S., Posada, R. & Riede, J.O. (2017) Evaluation of gridding procedures for air temperature over southern Africa. *Advances in Science and Research*, **14**, 163–173. CrossRef

Fadare, D.A. (2010) The application of artificial neural networks to mapping of wind speed profile for energy application in Nigeria. *Applied Energy*, **87**, 934–942. CrossRef

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A. & Michaelsen, J. (2015) The climate hazards infrared precipitation with stations — a new environmental record for monitoring extremes. *Scientific Data*, **2**, article 150066. CrossRef

Helmschrot, J., Muche, G., Hillmann, T., Kanyanga, J., Butale, M., Nascimento, D., Kruger, S., Strohbach, B., Seely, M., Ribeiro, C., De Clercq, W., Kenabatho, P., Josenhans, K., & Jürgens, N. (2015) SASSCAL WeatherNet to support regional weather monitoring and climate-related research in Southern Africa. *Proceedings of the International Association of Hydrological Sciences*, **366**, 170–171. CrossRef

IPCC (2015) *Climate change 2014 – synthesis report*. http://www.ipcc.ch/report/ar5/syr/

Jürgens, N., Haarmeyer, D.H., Luther-Mosebach, J., Dengler, J., Finckh, M. & Schmiedel, U. (2010) *Biodiversity in southern Africa 1: patterns at local scale — the BIOTA Observatories*. Klaus Hess Publishers, Göttingen & Windhoek.

Kaspar, F., Helmschrot, J., Mhanda, A. et al. (2015) The SASSCAL contribution to climate observation, climate data management and data rescue in Southern Africa. *Advances in Science and Research*, **12**, 171–177. CrossRef

Kenabatho, P.K., Parida, B.P. & Matlhodi, B. (2018) Linking scientific research to development agenda: the case of a hydrometeorological project in the Notwane catchment, Botswana. *Handbook of Research on Geospatial Science and Technologies*, pp. 374–391. IGI Global, Hershey. CrossRef

Kumwenda, B., Mwaku, W., Mulongoti, D. & Louie, H. (2017) Integration of solar energy into the Zambia power grid considering ramp rate constraints. *2017 IEEE PES-IAS PowerAfrica Conference Proceedings*, 254–259. CrossRef

McNally, A., Arsenault, K., Kumar, S., Shukla, S. Peterson, P., Wang, S., Funk, C., Peters-Lidard, C.D. & Verdin, J.P. (2017) A land data assimilation system for sub-Saharan Africa food and water security applications. *Scientific Data*, **4**, article 170012. CrossRef

Meyer, H., Drönner, J. & Nauss, T. (2017) Satellite-based high-resolution mapping of rainfall over southern Africa. *Atmospheric Measurement Techniques*, **10**, 2009–2019. CrossRef

Navarro, A., Rolim, J., Miguel, I., Catalão, J., Silva, J., Painho, M. & Vekerdy, Z. (2016) Crop monitoring based on SPOT-5, Take-5, and Sentinel-1A data for the estimation of crop water requirements. *Remote Sensing*, **8**, 525. CrossRef

Omer, A.M. (2008) On the wind energy resources of Sudan. *Renewable and Sustainable Energy Reviews*, **12**, 2117–2139. CrossRef

Posada, R., Nascimento, D., Neto, F.O.S., Riede, J. & Kaspar, F. (2016) Improving the climate data management in the meteorological service of Angola: experience from SASSCAL. *Advances in Science and Research*. **13**, 97–105. CrossRef

Posada, R., Riede. J., Kaspar, F., Mhanda, A., Radithupa, M., Stegling, J., Nascimento, D., Tima, L., Nkonde, E., Swaswa, M. & Waitolo, D. (2018) Cooperation of meteorological services within SASSCAL on improving the management of observed climate data. This volume. CrossRef

Scherer, C., Jeltsch, F., Grimm, V. & Blaum, N. (2016) Merging trait-based and individual-based modelling: An animal functional type approach to explore the responses of birds to climatic and land use changes in semi-arid African savannas. *Ecological Modelling*, **326**, 75–89. CrossRef

Siepker, E.B.J. & Harms, T.M. (2017) On the potential value of interval-deficient wind data. *Journal of Wind Engineering and Industrial Aerodynamics,* **165**, 100–114. CrossRef

Strohbach, B.J. (2014) *The SASSCAL / MAWF Weather Stations Network in Namibia. Overview of equipment and data transfer*. Polytechnic of Namibia, Windhoek.

Strohbach, B.J. (2017) Vegetation of the Auas-Oanob Conservancy in the Khomas Hochland of Namibia. *Namibian Journal of Environment*, **1**, 14–33.

Strohbach, B.J. & Kutuahuripa, J.T. (2014) Vegetation of the Eastern Communal Conservancies in Namibia: II. Environmental drivers. *Koedoe — African Protected Area Conservation and Science*, **56**, 1–12. CrossRef

Van Holsbeeck, S., De Cauwer, V., De Ridder, M., Fichtler, E., Beeckman, H. & Mertens, J. (2016) Annual diameter growth of *Pterocarpus angolensis* (Kiaat) and other woodland species in Namibia. *Forest Ecology and Management*, **373**, 1–8. CrossRef

World Meteorological Organization (2011) *WMO guide to climatological practices*. WMO-No. 100. World Meteorological Organization, Geneva.

World Meteorological Organization (2012) *WMO guide to THE Global Observing System*. WMO-No. 488. World Meteorological Organization, Geneva.

Towards an integrated pan-African observation network for long-term climate change monitoring: A web-based tool for collaborative data collection and analysis

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Systematic and long-term observation of relevant environmental properties is a pre-condition not only to detect, understand and attribute climate change, but also for sound decision-making with regards to climate change adaptation, mitigation and food security. In the case of the African continent, there are still major observational gaps, resulting in major uncertainties for most of the key variables of climate change, above all the greenhouse gas balance (Valentini et al., 2014). SASSCAL, in collaboration with a range of partner institutions, is contributing to the closure of these gaps through the EU-funded project ‘Supporting EU-African Cooperation on Research Infrastructures for Food Security and Greenhouse Gas Observations’ (SEACRIFOG). The project (www.seacrifog.eu) aims to develop a road map towards a tailored network of research infrastructures covering the African continent for the long-term observation of climate change and related environmental dynamics. SASSCAL’s main contributions include the identification of essential variables and parameters to be captured by that network, an inventory of existing and planned research infrastructures as well as an assessment of corresponding data needs and gaps.

In order to integrate these tasks and facilitate a comprehensive consultative process which captures expert input from relevant researchers, SASSCAL developed the ‘SEACRIFOG Collaborative Inventory Tool’ (http://seacrifog-tool.sasscal.org/). This web-based tool allows for systematic capturing, sharing and visualization of information on variables, observation networks/infrastructures and existing data products as well as subsequent analysis. Registered contributors can access and use the tool to retrieve, add and edit information. In analogy to the identification of the set of essential climate variables (Bojinski, et al., 2014), a broad set of atmospheric, oceanic and terrestrial variables of potential relevance is identified in a first step. These variables are then assessed against their context-specific relevance as well as the feasibility and cost implications of their long-term measurement according to both locally appropriate and globally required standards. For the

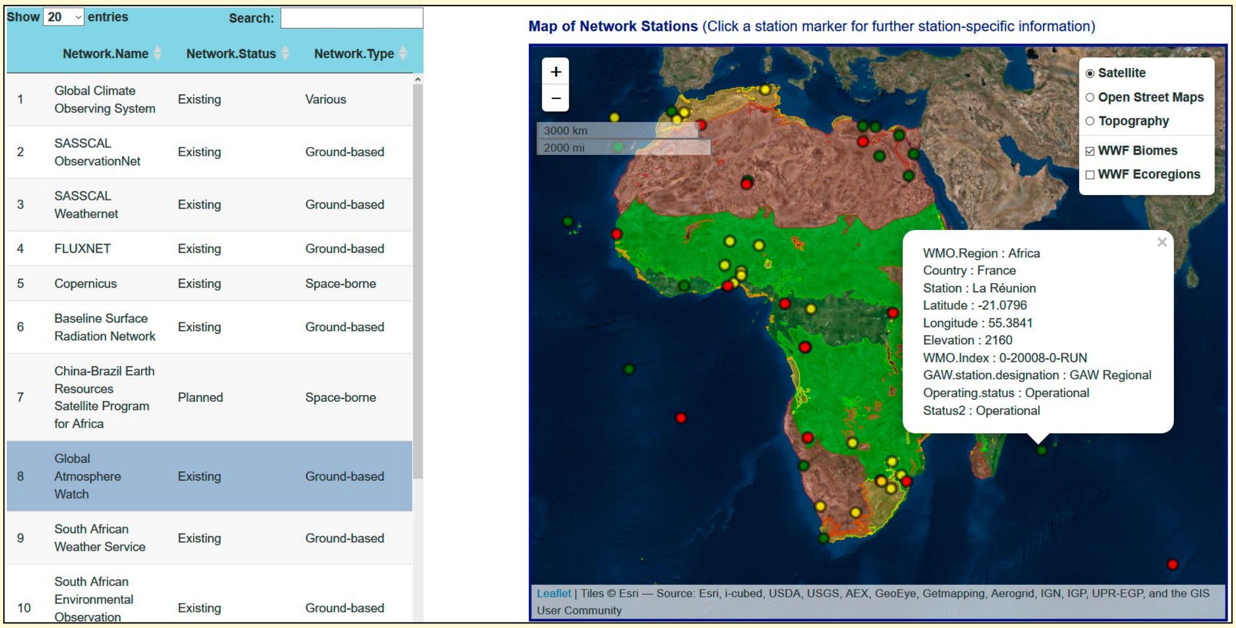

Figure 1: Screenshot of the SEACRIFOG Collaborative Inventory Tool, developed by SASSCAL in 2018.

resulting set of essential variables, existing and planned research infrastructures are identified. These can be both global networks such as the World Meteorological Organization's Global Atmosphere Watch (Fig. 1) as well as regional and local networks such as the SASSCAL WeatherNet (Muche et al., 2018) and the SASSCAL ObservationNet (Hillmann et al., 2018; Jürgens et al., 2018). Where applicable, individual sites are captured, which allows for spatial analysis to determine the geographic coverage with the specific purpose to ensure that greenhouse gas emission hotspots or climate-sensitive ecosystems be captured appropriately.

We consider this web-based tool a promising approach to pool the expertise and facilitate remote collaboration by a large group of environmental observation scientists towards the common goal of designing a regionally appropriate observation network which is fully interoperable with global initiatives. We further expect to draw valuable lessons from this collaborative process to further improve this tool and develop additional functionality. Future possibilities include expanding this approach to other applications and turning this tool into a publicly available resource, e.g. through integration with the SASSCAL Data and Information Portal (Helmschrot et al., 2018).

References:

Bojinski, S., Verstraete, M., Peterson, T. C., Richter, C., Simmons, A., & Zemp, M. (2014). The Concept of Essential Climate Variables in Support of Climate Research, Applications, and Policy. *Bulletin of the American Meteorological Society*, **95**, 1431-1443.

Helmschrot, J., Thompson, S., Kralisch, S. & Zander, F. (2018). The SASSCAL Data and Information Portal. This volume.

Hillmann, T., Muche, G., Josenhans, K. & Jürgens, N. (2018). Online presentation of the SASSCAL ObservationNet. This volume.

Muche, G., Kruger, S., Hillmann, T. et al. (2018). SASSCAL WeatherNet: present state, challenges, and achievements of the regional climatic observation network and database. This volume.

Jürgens, N., Strohbach, B., Lages, F., Schmiedel, U., Finckh, M., Sichone, P., Marie Hahn, L.-M. & Zigelski, P. (2018) Biodiversity Observation – an overview of the current state and first results of biodiversity monitoring studies. This volume.

Valentini, R., Arneth, A., Bombelli, A., et al. (2014) A full greenhouse gases budget of Africa: synthesis, uncertainties, and vulnerabilities. *Biogeosciences*, **11**, 381-407.

Climate

Predictability of daily precipitation using data from newly established automated weather stations over Notwane catchment in Botswana

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Abstract: Already semi-arid, due to the effects of climate change, Botswana has been experiencing unreliable water supplies over the past several years. However, the limited climate information over different catchments makes engaging in an informed decision-making process difficult. The Notwane catchment at Gaborone dam, located in the headstreams of the Notwane River in eastern Botswana, is a major water supply for the country. However, due to the sparse network of hydro-meteorological measurement stations, no reliable predictions can be made and, thus, creating a reliable runoff estimation for the reservoir has been difficult. Through SASSCAL, an experimental set of automated weather stations has been set up in the Notwane catchment. Preliminary analysis using artificial neural networks (ANNs) to examine the predictive capacity of the monitored variables (from July 15, 2016, through June 25, 2017: 346 days) on precipitation at four individual stations reveals that the gathered hydro-meteorological data may be useful given an increase in record length coupled with consideration of different modeling approaches to validate inherent relationships with precipitation. Study also revealed that simulated precipitation for the area exhibits similar mean and variability to the observations despite poor simulations for extreme precipitation events. These results give insight into prospects for improved hydrologic and water resource modeling over the catchment.

Resumo: O Botswana semi-árido tem sofrido com um fornecimento incerto de água ao longo dos anos, devido aos impactos das alterações climáticas. Mesmo as informações climáticas escassas/limitadas das diferentes bacias hidrográficas dificultam o processo de tomada de uma decisão informada. A bacia hidrográfica de Notwane na barragem de Gaborone, localizada na nascente do Rio Notwane no Este do Botswana, é uma importante fonte de abastecimento de água no país. Porém, devido à esparsa rede de estações de medição hidrometeorológica, não foi possível fazer previsões fiáveis e, por isso, foi difícil estimar de forma segura a escorrência para o reservatório. Através do SASSCAL, foi criado um conjunto experimental de Estações Meteorológicas Automáticas na bacia de Notwane. Uma análise preliminar usando Redes Neuronais Artificiais (ANNs) na capacidade preditiva de variáveis monitorizadas (de 15/07/2016 a 25/06/2017: 346 dias) na precipitação em quatro estações individuais revela que os dados hidrometeorológicos poderão ser possivelmente úteis com o aumento do número de registos, juntamente com a consideração de diferentes abordagens de modelação para validações de relações inerentes com a precipitação. É também evidenciado que a precipitação simulada exibe uma média e variabilidade semelhantes às observadas, apesar das escassas simulações para eventos de precipitação extremos. Estes resultados dão-nos uma expectativa para uma melhor modelação dos recursos hídricos e hidrológicos na bacia hidrográfica.

Introduction

Gaborone, the capital city of Botswana, is the country's major population cluster, with accelerated rural-urban migrations to the city leading to increased water demand. As a result, the Notwane catchment, which is the main source of water for the city, has required inter-basin transfer of water from the relatively wet northeastern part of Botswana. However, transporting water over 500 km to supplement the Gaborone reservoir comes at great costs. Despite this, hydro-meteorological data availability regarding the catchment is almost nonexistent (Kenabatho et al., 2017). The very sparse stations over the catchment monitor only precipitation and temperature, and leave considerable data gaps. With the installation of automated weather stations (AWS)

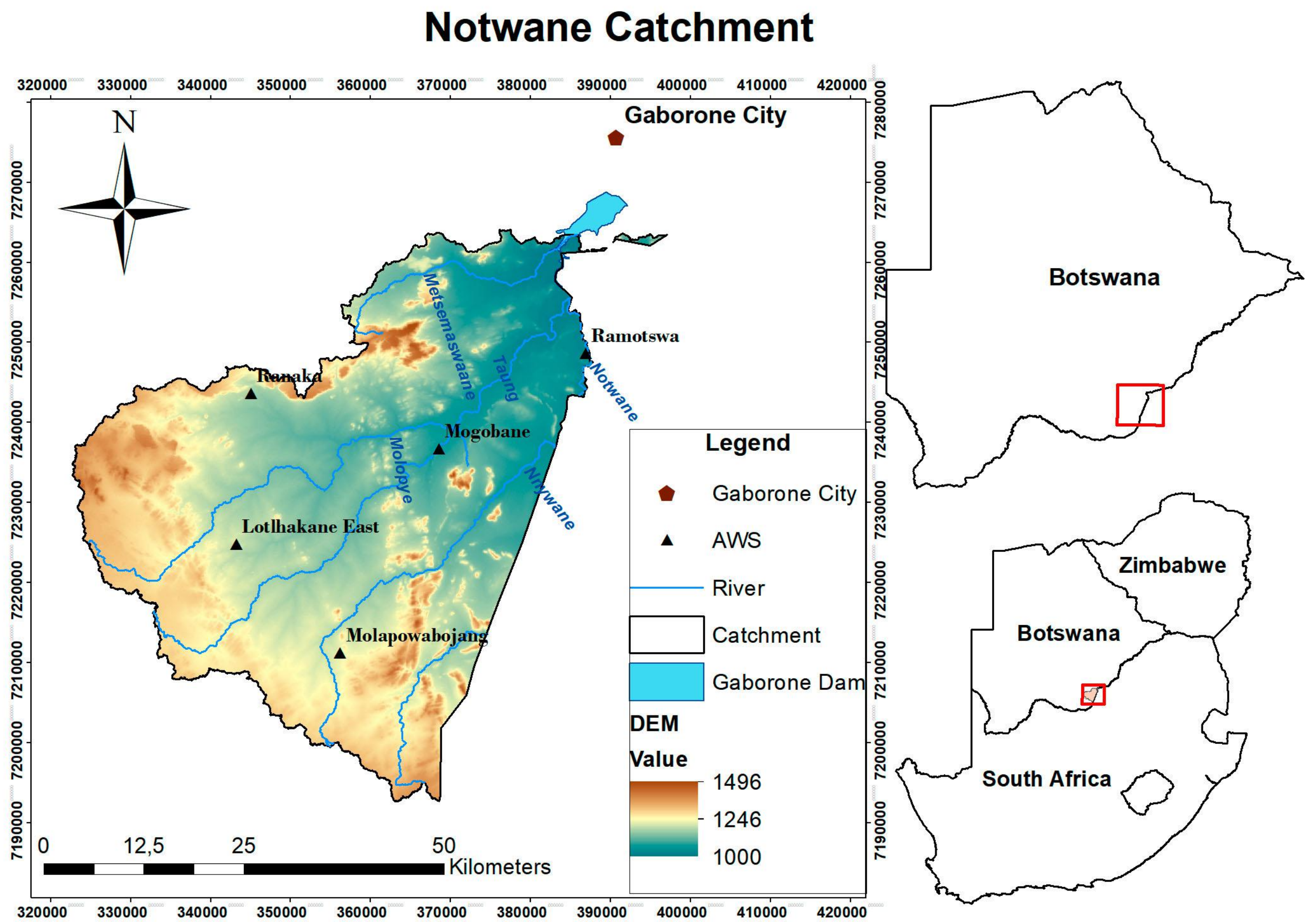

Figure 1: Locations of the automated weather stations (AWS) over Notwane catchment in Botswana.

made possible through the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) project, efforts towards improving hydro-meteorological monitoring to aid hydrologic modeling and river basin and water resource management could be realised. The weather stations are already operational and have alleviated the challenge of working with only limited, poor-quality data.

Artificial neural networks (ANNs), a computational tool based on the neural structure of brain systems, have been adopted for the study. ANNs have gained prominence in data science, being particularly useful in modelling the complex interactions between rainfall and runoff in flow regime studies. These are uniquely powerful tools in applications where formal analysis would be difficult or impossible, such as pattern recognition and nonlinear system identification and control (Furundzic, 1997; Anmala et al., 2000; Uvo et al., 2000; Sivakumar et al., 2002). ANNs were also found to be better than using the multiplicative autoregressive integrated moving average (MARIMA) when forecasting rainfall and temperature over Botswana (Kenabatho et al., 2015). Non-linearity is a prime characteristic of issues related to the atmospheric and hydrologic sciences and thus, ANNs are ideally suited for such problems because, like their biological counterparts, a neural network can learn, and therefore can be trained to find solutions, recognise patterns, classify data, and even forecast future events (Hsu et al., 2002; Parida & Moalafhi, 2008; Kenabatho et al., 2015). The feedforward multi-layer architectures of ANNs have been shown to have computational superiority in comparison to other paradigms (Adeloye & Munari, 2006; Parida et al., 2006; Kenabatho et al., 2015).

The main aim of this paper is to test the utility of the hydro-meteorological variables from the newly developed SASSCAL AWS in modelling rainfall by way of establishing and using the relationships between the measured independent/predictor variables (i.e,. temperature and humidity) and the predictand/target variable (rainfall). This will assist in improved simulation of rainfall events at these sites, especially during instances when rainfall data become unavailable as a result of malfunctions by rainfall recorders, among other situations. The model results will also give an indication of the data's potential utility for simulating rainfall events, urgently needed for future water resources planning. It is anticipated that future operation and maintenance of the AWS, supplemented with streamflow gauging, will help to improve hydrologic and water resources modelling and, therefore, improve water resources management over the highly urbanised Notwane catchment of Botswana. The catchment, with improved monitoring, will also play an important role as an experimental basin for teaching regarding hydrology and water resources management, especially at the University of Botswana.

Climate

Methods

Study site

The catchment is located upstream of the Gaborone dam within the south-east district, and within close proximity to Gaborone, the capital of Botswana (Fig. 1). Its spatial extent is longitude 25.5°E to 26.0°E, and latitude 24.5°S to 25.5°S. Due to its proximity to the capital and the associated 'pull factors of modernity', there have been rapid land use changes and increased demand for water with implications for runoff generation and water supply, respectively. In 1991, census data showed that about 50% of Botswana's population lived within a 100 km radius of the capital, Gaborone (CSO, 2001). Inhabitants of Gaborone and its immediate surroundings within the Notwane catchment have become more affluent, which, coupled with the boom in population over the catchment, has led to an ever-increasing per-capita water demand (Moalafhi et al., 2012).

The Notwane, Taung, Metsemaswaane, and Nywane rivers drain the area. These rivers are intermittent due to the semi-arid conditions of the region. The catchment experiences annual rainfall averaging 500 mm, with high mean annual temperatures averaging 25°C that lead to high evaporation rates. Rainfall, as is the case for the rest of the country, is seasonal. Rains mostly start around November and end in April.

Data

Six variables are considered at daily time steps from 15 July 2016 to 25 June 2017 (346 days) from four out of a total of five AWS over Notwane catchment in Botswana. Only four stations were chosen based on data availability. The variables are precipitation (mm); temperature (maximum, average, and minimum in °C); relative humidity (%); and global radiation (mJ/km^2). Currently, there is no river discharge monitoring over the catchment; thus, precipitation is being used as a key hydro-meteorological variable with implications for runoff generation at the atmosphere-biosphere interface. Precipitation is therefore being used as a proxy for river discharge; it is also used for demonstration purposes regarding the predictive capacity of the AWS variables among themselves. For this reason, the measured rainfall values (dependent variable) together with temperature (minimum, average, and maximum), relative humidity, and global radiation (independent/predictor variables) are used to develop an ANN model structure to simulate rainfall for the catchment. The model is run for each of the four AWS stations—Ranaka, Mogobane, Molapowabojang, and Lotlkhakane East—to assess the predictability of rainfall at locations of the newly established AWS.

Back-propagation artificial neural network (BPANN) modelling

The dependent variables are used as the inputs to the ANN model architecture, while precipitation is used as the output (target variable) being simulated. A multi-layer feedforward back-propagation ANN is adopted.

The back-propagation training algorithm begins by setting a set of random weights; during training, weights are iteratively modified on the basis of the differences between the training output and the desired output. To facilitate this, a rule or function $g(x)$ together with an initial value P_0 is set for computing successive terms. A sequence of values $\{P_k\}$ is then obtained using the iterative rule $P_{k+1} = g(P_k)$. In this case, an ANN is presented with inputs (here, five independent hydro-meteorological variables) and the target variable to be reproduced (precipitation in this case). The network is then trained to learn the relationships between the input variables and the target variable, with the ultimate aim of reproducing the target variable (precipitation) based on the learned relationships. The structure of the ANN topology adopted in this study is shown in Figure 2; it consists of five input variables (predictors), 25 neurons for processing the information, and one output neuron for the target precipitation (predictant).

The Levenberg–Marquardt (L-M) algorithm, which is commonly used for back-propagation algorithm training (Hagan & Menhaj, 1994; Samani et al., 2007), is adopted in this study. Early stopping is implemented by dividing data randomly into three subsets: training, validation and testing (Adeloye & Munari, 2006). Selecting the three subsets randomly helps accommodate a reasonable range of extreme events, which helps to make good predictions (Minns & Hall, 2004; Thirumalaiah & Deo, 1998). The training set is used for computing the gradient and updating the network weights and biases, in which the error on the validation set is monitored during the training process. When the validation error increases for some specified and/or default number of iterations, training is stopped and the weights and biases at the minimum of the validation error are returned. The model is then ready to be tested using the remaining dataset. The log-sigmoidal is used for the hidden layer neurons and the linear transfer function is used for the output layer neuron.

For model performance evaluation, the closeness of fit of the simulated precipitation to the observed precipitation is assessed through Pearson correlation coefficient (r) and mean squared error (MSE). The Pearson correlation coefficient (r-value) evaluates the goodness of fit by performing linear regression between the predicted and target precipitation, while mean squared error is the average sum of squares of the difference between predictions and targets.

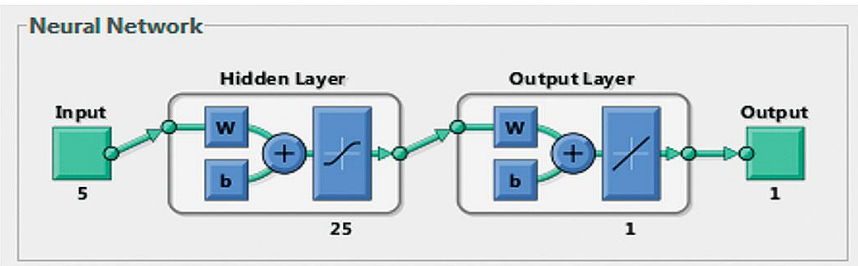

Figure 2: The ANN structure showing the average optimum network architecture that was adopted with five (5) input layers and twenty-five (25) hidden layer neurons (where a hidden layer neuron is a neuron whose output is connected to the inputs of other neurons and is therefore not visible as a network output; W and b represent weights and activity patterns, respectively, assigned to the independent variables).

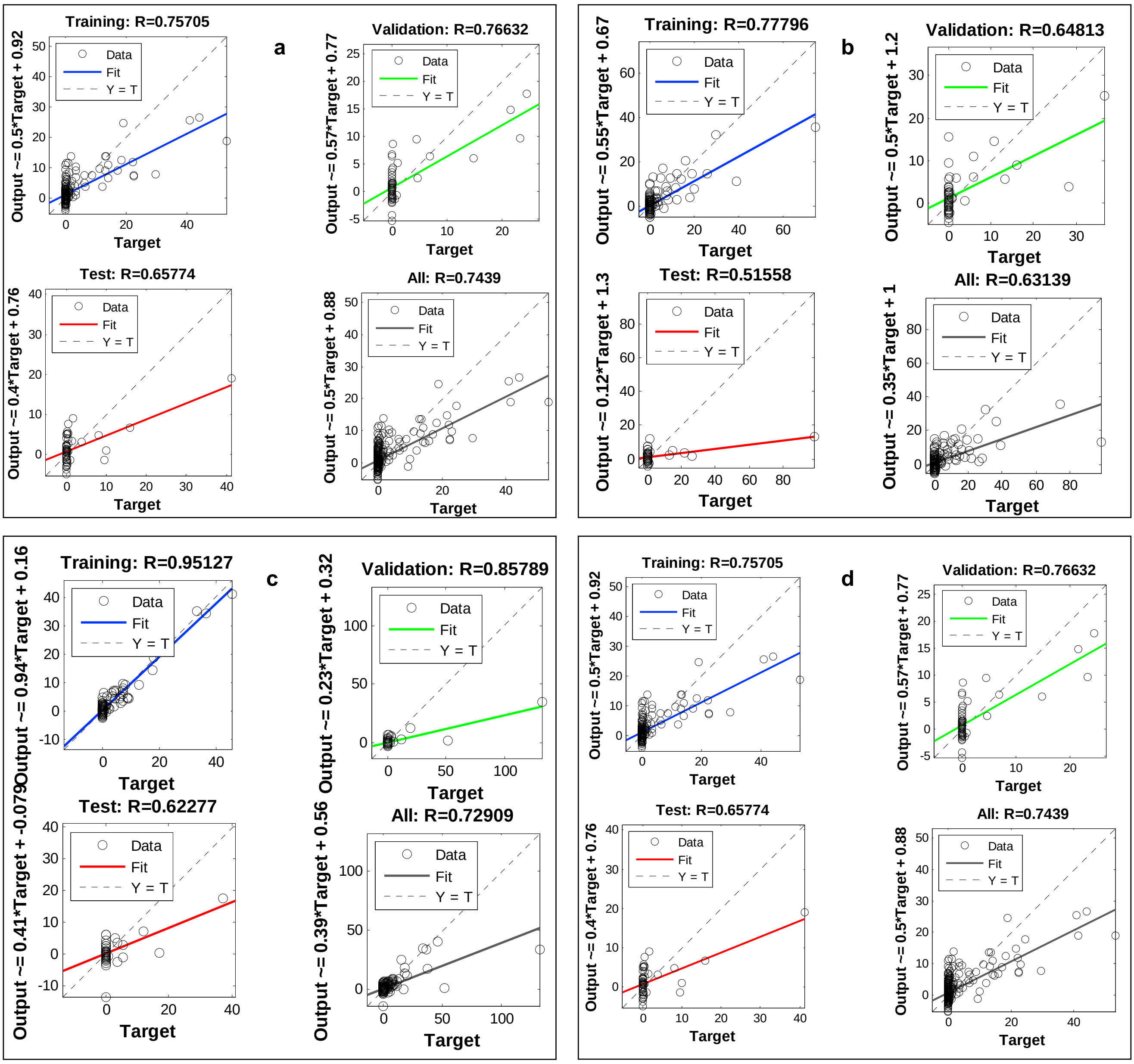

Figure 3: Correlation coefficients of precipitation simulations with observations for (a) Ranaka; (b) Mogobane; (c) Molapowabojang; and (d) Lotlhakane East.

Results

For each station (Fig. 3), four plots are given for model performance through correlation coefficient of the predicted precipitation and the observed precipitation during training, validation, and testing and when all the three subsets are combined together. The individual plots are labeled 'Training', 'Validation', 'Test', and 'All', showing blue, green, red, and grey best linear fit lines, respectively. The dotted lines show how the best-fit lines would appear for correlation coefficients of 1.

Each plot shows the observed precipitation as the target ('Target' or 'T') on the x-axis and the predicted precipitation ('Output' or 'Y') on the y-axis. The label of the y-axis shows the equation of the best linear fit relating the predicted precipitation (Output) and the observed precipitation (Target). The predictions show correlation coefficients well over 0.5 at all the stations. The highest correlation (0.85) was achieved at Lotlhakane East and the lowest (0.63) at Mogobane, considering the three subsets combined (Tab. 1).

Table 1: Summary performance of precipitation simulations at the individual stations over the catchment. r= correlation coefficient, rcomb. = r for combined data set; MSE = root mean square error (mm).

Statistic	Ranaka			Mogobane			Molapowabojang			Lotlhakane East		
	Training	Validation	Testing	Training	Validation	Testing	Training	Validation	Testing	Training	Validation	Testing
r	0.76	0.77	0.66	0.78	0.52	0.82	0.95	0.86	0.62	0.88	0.90	0.82
$r_{comb.}$		0.74			0.63			0.73			0.85	
MSE		13.53			28.26			24.04			17.42	

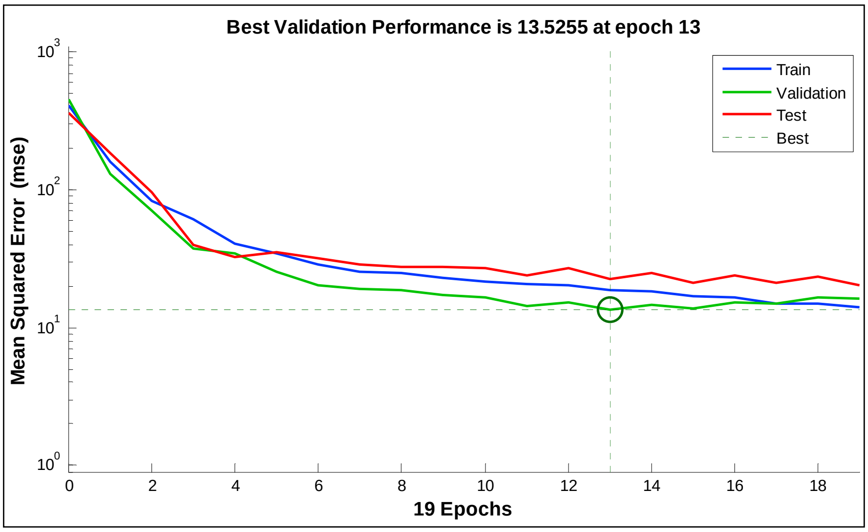

Figure 4: Performance of simulations during training, validation, and testing using mean squared error (MSE) for Ranaka station.

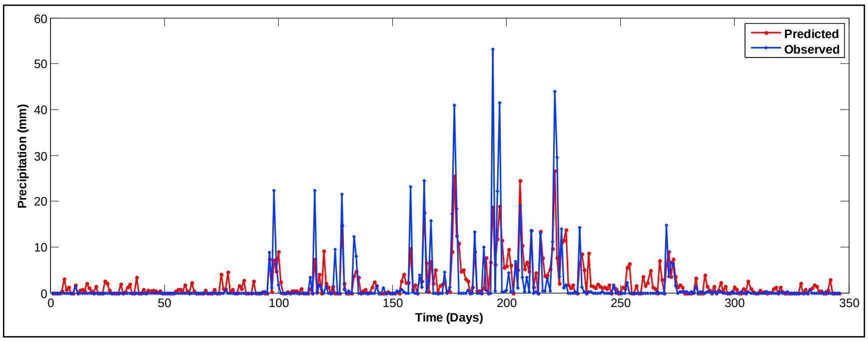

Figure 5: Observed and simulated precipitation at Ranaka station showing deteriorating performance especially for low precipitation events. Blue = observed precipitation; red = predicted precipitation.

Mean squared error (MSE), based on the validation component, showed that the best predictions were obtained at Ranaka station, while Mogobane displayed the worst performance (Tab. 1). An example of performance using MSE is shown in Figure 4, taken from Ranaka station, which shows performance during training, validation, and testing before the model convergence. The minimisation of error during the model run is shown for the three subsets of 'Training', 'Validation', and 'Testing'. These are shown in blue, green, and red, respectively. The minimum validation error during the model run was achieved after 13 epochs (iterations) with MSE of 13.5, as shown by Figure 4. Using Ranaka station as an example, low and high precipitation events are simulated relatively poorly (Fig. 5). Here, the predicted precipitation is shown in red while the observed precipitation is shown in blue.

Discussion

The hydro-meteorological variables did not predict precipitation very well at the individual stations (Tab. 1). In particular, extreme precipitation events (e.g., very low and very high amounts of rainfall) were predicted poorly. This poor performance might be a result of limitations of the model itself, and possibly due to the short length of data records (less than one year). As can be seen from the correlation plots (Fig. 3), there is a possibility that the network architecture is not learning the relationships sufficiently, as is especially visible with its failure to simulate extreme precipitation events well (Fig. 5). The model also demonstrates some challenges in differentiating between rain and no rain as shown in Figure 5. For most zero-rainfall events, the model predicted at least some rainfall. Despite these complications, training, validation, and testing runs converged closely as shown in Figure 5, where there are no noticeable improvements across the three data divisions in minimisation of mean squared error beyond 13 iterations.

There is another variation of the commonly used BPANN, the nonlinear autoregressive network with exogenous inputs (NARX), which appears to be gaining popularity in modelling processes related to climate sciences, including in semi-arid environments. Predictions made over longer time frequencies like months and the addition of more exogenous variables of precipitation with consideration of lag times have been found to significantly improve precipitation predictions using the NARX (Abarhouei and Hosseini, 2016). NARX is an important class of discrete-time nonlinear systems which predicts a current value of a time series based on current and past values of the exogenous series (Safavieh et al., 2007). Byakatonda et al. (2016) used the NARX to forecast dryness severity over the iconic Okavango Delta in Botswana with impressive model performance. Thus, this ANN variant configuration could be considered in the future.

Some correlations between the predicted and observed precipitation are below 0.60 in certain instances. These correlations were, however, found to be statistically significant, as they are greater than the p-critical values at 0.05 significance level. Simulations at Molapowabojang station are almost joint second best with those at Ranaka station in terms of reproducing temporal correlations between predicted and observed precipitation. Reproduction of precipitation mean via the simulations at Mogobane station is slightly worse than at the rest of the stations, with mean squared error of 28.26. All the stations are within the influence of the easterlies, and this could partly explain the similarities in performance of the model across the stations. Notably, rankings of performance of the model at the individual stations differ between MSE and temporal correlation. It is thus important to always use both mean and variability performance measures in evaluating simulations. In this regard, recommendations can be made on suitability of simulations for both mean and variability individually and collectively (Moalafhi et al., 2016).

Inclusion of other independent predictors like El Niño Southern Oscillations (ENSO), and reanalysis precipitation and temperature data may possibly improve simulation of extreme events (Kenabatho et al., 2012). It would also be interesting to determine how much of total variation in precipitation each individual hydro-meteorological predictor variable contributes. Through principal component analysis, it would be important to remove redundant input variables for improved efficiency if more exogenous variables with some delayed times are to be considered.

Conclusion

The modelling exercise revealed that the chosen modeling framework using ANNs was suitable for this catchment. However, precipitation is not simulated very well at each individual station. Predicted precipitation was found to exhibit similar mean and variability with the observations. However, stations for which precipitation variability was simulated best do not necessarily show the best precipitation mean simulations, emphasising the need to use both mean and variability performance measures in assessing simulations. Simulations tend to deteriorate towards low and high precipitation events. During the refinement of this work, other model algorithms will be tested.

These results give some insight into the challenges of short time series and limited numbers of predictor variables, as well as illustrating the need for further reflection on which model algorithm is best suited to the situation being evaluated. Furthermore, exogenous variables like ENSO, reanalysis temperature, and precipitation should be incorporated to improve the simulations. With improvements, AWS data could be used to simulate future rainfall, assisting in cases where measurements may not be available, as is common in monitoring networks. Ultimately, this will support hydrological modeling applications and water resource management over the catchment.

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References

Abarghouei, H.B. & Hosseini, S.Z. (2016) Using exogenous variables to improve precipitation predictions of ANNs in arid and hyper-arid climates. *Arabian Journal of Geosciences,* **9**, 663.

Adeloye, A.J., & de Munari, A. (2006) Artificial neural network-based generalised storage-yield-reliability models using the Levenberg-Marquardt algorithm. *Journal of Hydrology,* 362, 215-230.

Anmala, J., Zhang, B. & Govindaraju, R.S. (2000) Comparison of ANNs and empirical approaches for predicting watershed runoff. *Journal of Water Resources Planning and Managment,* **126**, 156-166.

Byakatonda, J., Parida, B.P., Kenabatho, P.K.,& Moalafhi, D.B. (2016) Modeling dryness severity using artificial neural networks at the Okavango Delta, Botswana. *Global NEST Journal,* **18**, 463-481

Central Statistics Office. (2001) *Population and Housing Census Preliminary Brief.* Statistics Botswana, Gabarone, Botswana.

Coulibaly, P., Anctil, F., Aravena, R. & Bobée, B. (2001) Artificial neural network modelling of water table depth fluctuations. *Water Resources Research,* **37**, 885-896.

Furundzic, D. (1997) Application example of neural networks for time series analysis: Rainfall runoff modelling. *Signal Processing,* **64**, 383-396.

Hagan, M.T., & Menhaj, M.B. (1994) Training feedforward networks with the Marquardt algorithm. *IEEE Transactions on Neural Networks,* 5, 989-993.

Hsu, K., Gupta, H.V., Gao, X., Sorooshian, S. & Imam, B. (2002) Self-organising linear output map (SOLO): An artificial neural network suitable for hydrologic modelling and analysis. *Journal of Hydrology,* **38**, 1-17.

Johnson, V.M. & Rogers, L.L. (2000) Accuracy of neural network approximators in simulation optimisation. *Journal of Water Resources Planning and Management,* **126**, 48-56.

Kenabatho P.K., Parida B.P. & Moalafhi D.B. (2012) The value of large-scale climate variables in climate change assessment: The case of Botswana's rainfall. *Physics and Chemistry of the Earth* **50-52**, 64-71.

Kenabatho P.K., Parida B.P., Moalafhi D.B., & Segosebe T. (2015) Analysis of rainfall and large-scale predictors using a stochastic model and artificial neural network for hydrological applications in southern Africa. *Hydrological Sciences Journal*, **60**, 1943-1955.

Kenabatho P.K., Parida, B.P. Moalafhi D.B., & Matlhodi B. (2017) Linking scientific research to development agenda: The case of a hydro-meteorological project in the Notwane catchment. *Handbook of Research on Geospatial Science and Technologies* (ed. by J.G. Maphanyane & R. Mapeo), pp. 374–391. IGI Global, Hershey, Pennsylvania.

Lischeid, G. (2001) Investigating short-term dynamics and long-term trends of SO4 in the runoff of a forested catchment using artificial neural networks. *Journal of Hydrology,* **243**, 31-42.

Minns, A.W. & Hall, M.J. (2004) Rainfall-runoff modeling. *Neural Networks for Hydrological Modeling* (ed. by R.J. Hart, P.E. Kneale, & L.M. See), pp. 157–176. A.A. Balkema Publishers, Leiden, the Netherlands.

Moalafhi D.B., Evans J.P. & Sharma A. (2016) Evaluating global reanalysis datasets for provision of boundary conditions in regional climate modelling. *Climate Dynamics: Observational, theoretical and computational research on the climate system,* pp. 1-19, http://dx.doi.org/10.1007/s00382-016-2994-x.

Moalafhi D.B., Parida B.P., & Kenabatho P.K. (2012) New population forecasting techniques for realistic water demand management in urban centres of Botswana. Proceedings of the IASTED International Conference on Science and Technology: A Platform for Sustainable Development, Gaborone, pp191-197 (in CD).

Parida, B.P. & Moalafhi, D.B. (2008) Regional rainfall frequency analysis for Botswana using L-moments and radial basis function network. *Physics and Chemistry of the Earth,* **33**, 614-620.

Parida B.P., Moalafhi D.B. & Kenabatho P.K. (2006) Forecasting runoff coefficients using ANN for water resources management: The case of Notwane catchment in eastern Botswana. *Physics and Chemistry of the Earth,* **31**, 928-934.

Safavieh, E., & Andalib, S.A. (2007) Forecasting the unknown dynamics in NN3 database using a nonlinear autoregressive recurrent neural network. *International Joint Conference on Neural Networks*, pp. 2105-2109.

Sahoo, G.B., & Ray, C. (2006) Flow forecasting for Hawaii stream using rating curves and neural networks. *Journal of Hydrology,* 317, 63-80.

Samani, N., Gohari-Moghadam, M., & Safavi, A.A. (2007) A simple neural network model for the determination of aquifer parameters. *Journal of Hydrology,* 340, 1-11.

Shamseldin, A.Y. (1997) Application of a neural network technique to rainfall-runoff modelling. *Journal of Hydrology,* **199**, 272-294.

Sivakumar, B., Jayawardena, A.W. & Fernando, T.M.K.G. (2002) River flow forecasting: Use of phase-space reconstruction and artificial neural networks approaches. *Journal of Hydrology,* **265**, 225-245.

Thirumalaiah, K., & Deo, M.C. (1998) River stage forecasting using artificial neural networks. *Journal of Hydrologic Engineering,* 3, 26-32.

Uvo, C.B., Tolle, U. & Berndtsson, R. (2000) Forecasting discharge in Amazon using artificial neural networks. *International Journal of Climatology,* **20**, 1495-1507.

References [CrossRef]

Abarghouei, H.B. & Hosseini, S.Z. (2016) Using exogenous variables to improve precipitation predictions of ANNs in arid and hyper-arid climates. *Arabian Journal of Geosciences*, **9**, 663. CrossRef

Adeloye, A.J., & de Munari, A. (2006) Artificial neural network-based generalised storage-yield-reliability models using the Levenberg-Marquardt algorithm. *Journal of Hydrology*, **362**, 215-230. CrossRef

Anmala, J., Zhang, B. & Govindaraju, R.S. (2000) Comparison of ANNs and empirical approaches for predicting watershed runoff. *Journal of Water Resources Planning and Managment*, **126**, 156-166. CrossRef

Byakatonda, J., Parida, B.P., Kenabatho, P.K.,& Moalafhi, D.B. (2016) Modeling dryness severity using artificial neural networks at the Okavango Delta, Botswana. *Global NEST Journal*, **18**, 463-481

Central Statistics Office. (2001) *Population and Housing Census Preliminary Brief*. Statistics Botswana, Gabarone, Botswana.

Coulibaly, P., Anctil, F., Aravena, R. & Bobée, B. (2001) Artificial neural network modelling of water table depth fluctuations. *Water Resources Research*, **37**, 885-896. CrossRef

Furundzic, D. (1997) Application example of neural networks for time series analysis: Rainfall runoff modelling. *Signal Processing*, **64**, 383-396. CrossRef

Hagan, M.T., & Menhaj, M.B. (1994) Training feedforward networks with the Marquardt algorithm. *IEEE Transactions on Neural Networks*, **5**, 989-993. CrossRef

Hsu, K., Gupta, H.V., Gao, X., Sorooshian, S. & Imam, B. (2002) Self-organising linear output map (SOLO): An artificial neural network suitable for hydrologic modelling and analysis. *Journal of Hydrology*, **38**, 1-17.

Johnson, V.M. & Rogers, L.L. (2000) Accuracy of neural network approximators in simulation optimisation. *Journal of Water Resources Planning and Management*, **126**, 48-56. CrossRef

Kenabatho P.K., Parida B.P. & Moalafhi D.B. (2012) The value of large-scale climate variables in climate change assessment: The case of Botswana's rainfall. *Physics and Chemistry of the Earth* **50-52**, 64-71. CrossRef

Kenabatho P.K., Parida B.P., Moalafhi D.B., & Segosebe T. (2015) Analysis of rainfall and large-scale predictors using a stochastic model and artificial neural network for hydrological applications in southern Africa. *Hydrological Sciences Journal*, **60**, 1943-1955. CrossRef

Kenabatho P.K., Parida, B.P. Moalafhi D.B., & Matlhodi B. (2017) Linking scientific research to development agenda: The case of a hydro-meteorological project in the Notwane catchment. *Handbook of Research on Geospatial Science and Technologies* (ed. by J.G. Maphanyane & R. Mapeo), pp. 374–391. IGI Global, Hershey, Pennsylvania.

Lischeid, G. (2001) Investigating short-term dynamics and long-term trends of SO4 in the runoff of a forested catchment using artificial neural networks. *Journal of Hydrology*, **243**, 31-42. CrossRef

Minns, A.W. & Hall, M.J. (2004) Rainfall-runoff modeling. *Neural Networks for Hydrological Modeling* (ed. by R.J. Hart, P.E. Kneale, & L.M. See), pp. 157–176. A.A. Balkema Publishers, Leiden, the Netherlands. CrossRef

Moalafhi D.B., Evans J.P. & Sharma A. (2016) Evaluating global reanalysis datasets for provision of boundary conditions in regional climate modelling. *Climate Dynamics: Observational, theoretical and computational research on the climate system*, pp. 1-19. CrossRef

Moalafhi D.B., Parida B.P., & Kenabatho P.K. (2012) New population forecasting techniques for realistic water demand management in urban centres of Botswana. Proceedings of the IASTED International Conference on Science and Technology: A Platform for Sustainable Development, Gaborone, pp191-197 (in CD). CrossRef

Parida, B.P. & Moalafhi, D.B. (2008) Regional rainfall frequency analysis for Botswana using L-moments and radial basis function network. *Physics and Chemistry of the Earth*, **33**, 614-620. CrossRef

Parida B.P., Moalafhi D.B. & Kenabatho P.K. (2006) Forecasting runoff coefficients using ANN for water resources management: The case of Notwane catchment in eastern Botswana. *Physics and Chemistry of the Earth*, **31**, 928-934. CrossRef

Safavieh, E., & Andalib, S.A. (2007) Forecasting the unknown dynamics in NN3 database using a nonlinear autoregressive recurrent neural network. *International Joint Conference on Neural Networks*, pp. 2105-2109. CrossRef

Sahoo, G.B., & Ray, C. (2006) Flow forecasting for Hawaii stream using rating curves and neural networks. *Journal of Hydrology*, **317**, 63-80. CrossRef

Samani, N., Gohari-Moghadam, M., & Safavi, A.A. (2007) A simple neural network model for the determination of aquifer parameters. *Journal of Hydrology*, **340**, 1-11. CrossRef

Shamseldin, A.Y. (1997) Application of a neural network technique to rainfall-runoff modelling. *Journal of Hydrology*, **199**, 272-294. CrossRef

Sivakumar, B., Jayawardena, A.W. & Fernando, T.M.K.G. (2002) River flow forecasting: Use of phase-space reconstruction and artificial neural networks approaches. *Journal of Hydrology*, **265**, 225-245. CrossRef

Thirumalaiah, K., & Deo, M.C. (1998) River stage forecasting using artificial neural networks. *Journal of Hydrologic Engineering*, **3**, 26-32. CrossRef

Uvo, C.B., Tolle, U. & Berndtsson, R. (2000) Forecasting discharge in Amazon using artificial neural networks. *International Journal of Climatology*, **20**, 1495-1507. CrossRef

Water research in southern Africa: Data collection and innovative approaches towards climate change adaptation in the water sector

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Abstract: Water availability continues to hamper southern African nations' economic and societal development efforts. Highly variable rainfall; observed and projected rainfall decrease; and the inability of governments to keep up with infrastructure provision for fast-growing populations and urban, agricultural, and industrial sectors; as well as a lack of sufficient information and monitoring are some of the factors that limit the ability of decision-makers to manage water resources sustainably to promote social and economic development. Proper planning and management of water resources are not possible without a sufficient understanding and assessment of interacting drivers and processes controlling and/or affecting the water system. Against this background, the water theme of the SASSCAL programme aimed to significantly contribute to the knowledge base of southern African water resources, providing decision-makers with additional means to inform their planning efforts and thereby improve access to water, water resources management, and sustainable water use. Extensive research was conducted in Angola, Botswana, Namibia, South Africa, and Zambia, as well as across national borders. The focus was on improving monitoring and hydro-climatic data generation; gaining a better understanding of groundwater and surface water dynamics; and exploring the interdependency of water resources, water-use patterns, and vulnerabilities of society; as well as improving modelling techniques for advanced (transboundary) water resources assessment and management. This paper provides an overview of the SASSCAL water-related tasks to highlight some of the outcomes achieved under the SASSCAL water theme. Some key outcomes include: new methods for groundwater prospecting developed in

Namibia; socioeconomic studies to enhance integrated drought management in Namibia and Angola; improved accuracy in modelling in South Africa; a better understanding and monitoring of water quality in the Okavango Delta; updated digital geological maps in Angola; comprehensive river basin assessments; and significantly improved knowledge of groundwater and surface water resources and the effects of climate and land use change thereon.

Resumo: A disponibilidade de água continua a dificultar os esforços de desenvolvimento económico e social das nações do Sul de África. A elevada variabilidade da precipitação, a diminuição da precipitação observada e projectada, a incapacidade dos governos em manter a disponibilização de infraestruturas para as populações em crescimento e os sectores urbano, agrícola e industrial, bem como a falta de informação e monitorização suficientes, são alguns dos factores que limitam os decisores na gestão sustentável dos recursos hídricos para o desenvolvimento social e económico. O planeamento e a gestão adequados deste recurso complexo não é possível sem uma compreensão suficiente destes factores. Neste contexto, o tema da água do programa SASSCAL teve como objectivo contribuir significativamente para a base de conhecimento dos recursos hídricos da África Austral, fornecendo aos decisores meios adicionais para informar os seus esforços de planeamento e, assim, melhorar o acesso à água, a gestão dos recursos hídricos e o uso sustentável da água. Investigação extensiva foi realizada na África do Sul, Botswana, Namíbia, Angola e Zâmbia, bem como além fronteiras. O objectivo foi melhorar a monitorização e produção de dados hidro-climáticos, obter uma melhor compreensão das dinâmicas das águas subterrâneas e superficiais, explorar a interdependência dos recursos hídricos, padrões do uso da água e vulnerabilidades da sociedade, bem como melhorar técnicas de modelação para a avaliação e gestão avançada (transfronteiriça) dos recursos hídricos. Este artigo fornece uma visão geral das tarefas do SASSCAL relacionadas com a água, de modo a destacar alguns dos resultados alcançados sob este tema no SASSCAL. Alguns dos principais resultados incluem: novos métodos para a prospecção de águas subterrâneas desenvolvidos na Namíbia; estudos socioeconómicos para melhorar a gestão integrada da seca na Namíbia e Angola; maior precisão na modelação na África do Sul; uma melhor compreensão e monitorização da qualidade da água no Delta de Okavango; mapas geológicos digitais actualizados em Angola; avaliações abrangentes de bacias hidrográficas; melhoria significativa do conhecimento dos recursos hídricos subterrâneos e superficiais, e dos impactos do clima e uso das terras nos mesmos.

Introduction

The impact of climate change on water resources in southern Africa is already being experienced. Climate change, with a projected temperature increase of between 1.5°C and 3°C by 2050 (Niang et al., 2014), changes in rainfall patterns, and an intensification of climate extremes, will severely affect agricultural practices and food security in the region. The rapidly increasing intensity and severity of droughts and floods are catching the governments of these nations off guard. Never has this been more evident than in the current multiple-year drought that has been affecting southern African countries since 2014. The Southern African Development Community (SADC) declared the region a disaster area in 2016, due to nations being "overwhelmed" by the severity of the drought in 2015-2016 (SADC, 2016). As reported by the 2016 SADC Drought Fact Sheet, about 21.3 million people in the SADC region needed humanitarian assistance after losing their harvests to climate extremes and are now exposed to hunger, famine, and displacement. Moreover, Cape Town, South Africa, is currently fighting to not become the first coastal city in the world to run out of water (e.g., Schlanger, 2018). Ageing infrastructure, polluted water sources, a general lack of understanding of the hydrological response to climate change in catchments, and poor adaptive capacity are some of the factors that exacerbate the effects of below-average rainfall (Callaway, 2004; IPCC, 2007; Kusangaya et al., 2014). This interplay of natural hazards with inadequate infrastructure exposes the livelihoods of those in the region to ever-increasing risks (Taubenböck et al., 2018)—risks that demand improved management strategies. The coupling of technical-social perspectives towards risk management have been emphasised in the approach followed in SASSCAL (Taubenböck et al., 2009). The current drought has emphasised the urgent need to better understand the surface and groundwater resources of the region and their interaction with natural and human systems, as well as the pressures on these resources in terms of quality and quantity (Fig. 1), in order to support better planning and decision-making at the national and transboundary scales.

Weather and the atmosphere ignore national boundaries, as do fluxes of water, food, migrating people, and the spreading of animals and plants. Due to manifold ecological and socioeconomic processes and mechanisms of interaction, neighbouring countries are functionally interlinked at varying spatial and temporal scales. People living along watercourses are particularly affected. For instance, downstream riparian communities may depend on decisions taken by upstream users in a different country. Sustainable

Figure 1: Uncontrolled use of open water for domestic purposes with effects on water quality for downstream users in Menongue, Angola. (Photo: J. Helmschrot, 2013)

water resources management must consider trigger mechanisms, tipping points, and cascading effects at a regional or even larger scale. Numerous transboundary and regional agreements, institutions, commissions, and governance instruments have been or need to be established to jointly manage important water-related ecosystem resources and services and to develop novel, innovative utilisation options. All these examples strengthen the notion that, in addition to the local grassroots level and the national priority of informed political decision-making, it is essential to address the regional dimension of environmental change with validated, knowledge-based information.

All African SASSCAL countries have expressed the need for improved monitoring and enhancement of data collection network densities to increase water quality and quantity information to support improved decision making. However, such improved data needs to be supported by a better understanding of the drivers and processes of the water cycle controlling water-related ecosystem services. Additionally, more attention must be given to the role that groundwater resources at different depths could play as a strategic contingency resource during long-lasting droughts. Groundwater recharge estimation plays a crucial role for any sustainable management. Thus, water-related research activities in SASSCAL have been aimed at improving our knowledge of the complex interaction and feedback between surface and groundwater dynamics and resources, as well as land-surface processes in selected regions of SADC.

The main objective of this joint and integrated research effort of 17 water tasks was to develop reliable hydrological, hydro-climatic, and hydrogeological baseline data, along with a set of analytical methods to strengthen the research capacity of the water sector of the southern African region. With this in mind, the SASSCAL programme aimed to contribute to the implementation of integrated water resources management strategies for improved transboundary river management and resource usage in the context of global climate and land management changes.

The research activities within the water theme can be grouped into three key research areas:

- Baseline data observation/monitoring in Angola (new monitoring infrastructure establishments in the Rio Giraul Basin), Botswana (expansion of existing monitoring infrastructure in the Notwane Basin), Namibia (expansion of monitoring coverage in the Cuvelai-Etosha and Zambezi basins), and South Africa (continuation and extension of long-term observations in four catchments);
- Basic research in the fields of water quantity and quality assessments and modelling (with strong focus on the Barotse floodplain, Zambia, and the Okavango Delta), erosion and sedimentation assessments, and evaluation of land use/climate change impacts in selected river basins across the region; and
- Integrated and interdisciplinary research in the fields of groundwater mapping, water quality and quantity assessments and use, flood mapping, monitoring, risk assessments, and large-scale drought impacts, as well as analyses of water demand and water-related vulnerabilities of households.

In agreement with tasks from the other thematic areas, five regional hotspots were identified as locations for water research in the SASSCAL research portfolio (Fig. 2), while some studies used Earth-Observation (EO)-based products to monitor floods and droughts for the entire region (e.g., Müller et al., 2018). These locations were:

i. Northern Namibia/southern Angola (e.g., Cuvelai-Etosha Basin, Cunene Basin, Rio Giraul Catchment)
ii. Central Angola (Lusaka Province, Kwanza River Basin)
iii. The broader KAZA transboundary region, including the upper Zambezi River Basin, upper Congo River Basin, Okavango River Basin, and Chobe River Basin
iv. Southern Botswana (Notwane River Basin and upper Limpopo River Basin)
v. South Africa (Heuningnes, Verlorenvlei, and Sanspruit catchments in the Western Cape Province, Cathedral Peak in KwaZulu-Natal Province, and Letaba in Limpopo Province).

As a hypothesis for the SASSCAL water research, it is stated that improved monitoring and modelling will enhance the capacity in SADC to deal with water-related issues in a responsible manner. This paper primarily takes stock of the SASSCAL water research portfolio in the SASSCAL partner countries and provides a platform for ongoing and future research initiatives.

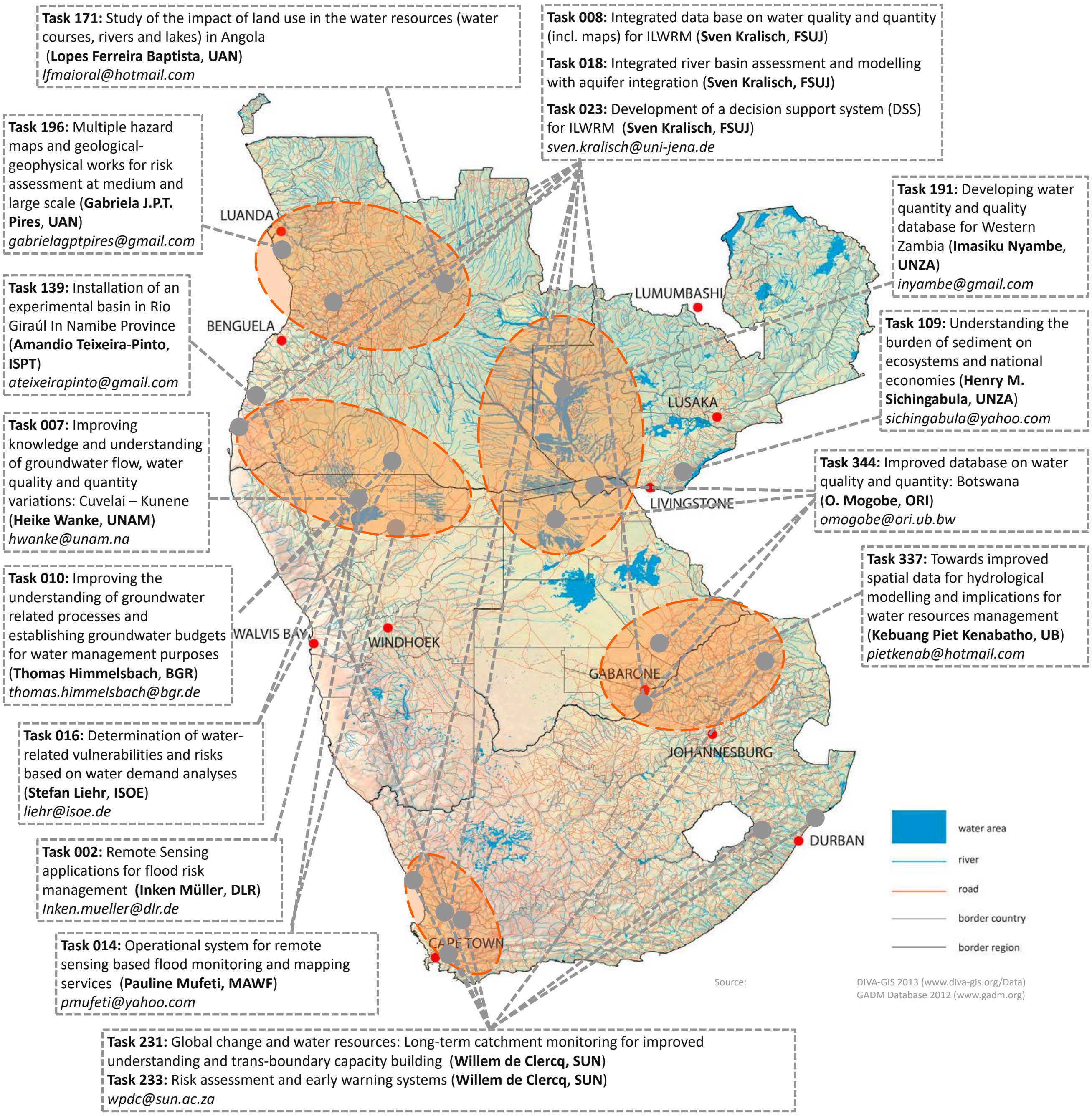

Figure 2: The locations of the SASSCAL water research sites.

Namibia

Groundwater will play an increasingly important role in ensuring water security for populations in arid and semi-arid regions amidst surface water decline due to climate change and population growth (Scanlon et al., 2006; Stadler et al., 2010). This is certainly the case for semi-arid southern Africa (MacDonald et al., 2012). Although it is recognised that southern Africa has significant potential for groundwater use (MacDonald et al., 2012), it is still critical to obtain sufficient information on the groundwater resources and impacts thereon to understand recharge patterns and ensure proper management of this finite resource. The complex interaction between land-use practices and groundwater quality needs to be understood before aquifers are intensively explored and utilised for human consumption or agriculture (Stadler et al., 2010; Bann & Wood, 2011) (Fig. 3).

Namibia is one of the driest countries in the world, which forced it to diversify its water sources and reduce dependency on surface water (Lahnsteiner & Lempert, 2007). Groundwater has long been in use and has occasionally been augmented by infiltration of treated waste water (Lahnsteiner & Lempert, 2007). Shallow aquifers are widely used because of their ease of access, but these are also often saline or contaminated due to land-use impacts. Himmelsbach et al. (2018) focused their research on exploring deep aquifer systems in Namibia in an attempt to improve the responsible use of groundwater resources in this country. The deeper, semi-fossilised systems present a more secure source of water

Figure 3: Extraction of shallow groundwater by wells with grazing livestock affecting groundwater quality in the Cuvelai region, Namibia. (Photo: J. Helmschrot, 2016)

for human use but studying these is as complex as accessing them for use. With their research, Himmelsbach et al. (2018) provide valuable insights into the methodology for groundwater prospecting in southern Africa. The focus was on creating a holistic strategy for groundwater exploration that is largely based on methods of oil and gas exploration. New scientific findings based on interdisciplinary research suggest the existence of further strategic groundwater resources that are related to large tectonic features on the continent, as well as intra-continental and coastal river deltas.

A second Namibian study provided an integrated assessment of the surface and groundwater quality and quantity in the Cuvelai-Etosha Basin. Wanke et al. (2018) conducted several field campaigns between 2013 and 2017 to obtain much-needed data required for more informed decision making in this transboundary catchment. Hydrological and microbiological sampling and analyses have shown that water quality and quantity in this region is highly variable, both in space and time. Knowledge of recharge conditions and recharge rates are indispensable key parameters for appropriate resource management, but only a few methods are applicable in arid environments. Stable isotope methods were intensively applied to quantify infiltration rates and evaporation loss and to better estimate recharge via the unsaturated zone (Beyer et al., 2016; Gaj et al., 2016). The complex interrelation of vegetation, soil structure, microclimate, and spatio-temporal heterogeneity were described as main regulators that govern deeper infiltration and net water fluxes. Both studies make practical recommendations for the implementation of corrective measures at a local scale that will improve water security in the region.

Luetkemeier & Liehr (2018) adopted a social-ecological perspective on water and food security and assessed the sensitivity of households to drought in the Cuvelai-Etosha Basin in Namibia and Angola (also see Luetkemeier et al., 2017). They conducted structured socioeconomic surveys in 2014 and 2015 among 461 households in urban and rural areas to assess seasonal water and food consumption patterns. The study found significant alterations of people's consumption patterns that serve as an entry point for drought sensitivity analyses. These insights contribute to an enhanced decision base for integrated drought risk management in both countries. The incorporation of the population's vulnerability is the key to upgrade common drought hazard assessments to integrated risk assessments. The study shows that people's coping capacities have to be assessed and evaluated against the specific drought hazard conditions.

The Hydrology Division in the Ministry of Agriculture, Water, and Forestry in Namibia uses a variety of systems for early flood warning and monitoring. These systems include telemetry gauges for rainfall and river levels, weather and rainfall forecasting systems, remote sensing for rainfall and river flow estimations, and satellite images for flood mapping and rapid assessments—all combined in empirical flood forecasting. Research was undertaken to improve the scientific basis for the implemented monitoring and observational systems. This was done by integrating EO technologies and hydrological and hydraulic modelling to determine surface water balances and conduct flood risk and vulnerability mapping in the target basin and floodplains. Results were combined in a scientifically sound flood model for the Cuvelai-Etosha Basin and the Namibian Zambezi floodplains. This was supported by field studies that analysed the target communities' vulnerability to floods caused by the possible impacts of increased climate variability and change. This was done to improve the ability to develop sound early warning and disaster risk management systems that will support local communities to cope with climate extremes. During the rainy season, early warning and flood forecasting information is disseminated through the Daily Flood Bulletin, which is provided to more than 600 stakeholders (Fig. 4).

With respect to short-term events such as floods, EO data, and particularly radar data, have been applied for the detection of surface water and thus, in exceptional circumstances, flooded areas (Müller et al., 2018). The developed object-based approach provides decision makers with mapping products of flooded areas 45 minutes after satellite data have been received. The combination of the spatial extent of the natural hazard and the exposed elements allows an assessment of people at risk (Müller et al., 2018).

South Africa

South Africa has a rich history in hydrological research concerning surface–groundwater interactions, rainfall-runoff modelling, the establishment of water resource databases, ecological reserve

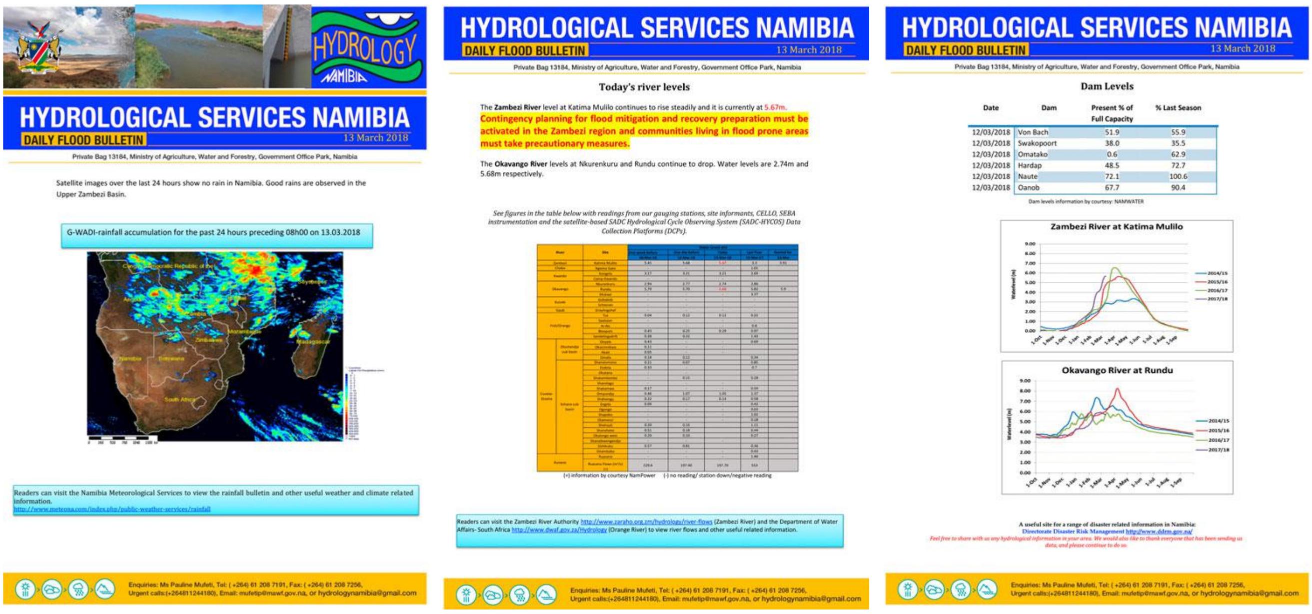

Figure 4: Daily Flood Bulletin of the Hydrology Division, Ministry of Agriculture, Water, and Forestry, serving more than 600 subscribers (MAWF, 2018).

determinations, and climate change impacts (Hughes, 2007). Nevertheless, there is lack of long-term monitoring in catchments, database systems for catchment water resources are scattered amongst different institutions and for different components of the water cycle, and there is a strong need to build capacity in the use of predictive hydrological models.

In South Africa, infrastructure related to water quantity and quality monitoring is the responsibility of the state. This infrastructure, for various reasons, started to become less important during the implementation phase of the new water legislation in South Africa, as the new law made room for Catchment Management Agencies (CMA) to be defined by the public and industry (Stein, 2005). The authority to monitor water was therefore increasingly transferred to the public domain, and during this period, the impacts of climate change and related problems in water became more topical. To make matters worse, at the onset of the SASSCAL research, South Africa also found itself in a crisis situation related to water supply and accountability related to mitigation of the ongoing drought (De Clercq et al., 2010).

Three universities, namely Stellenbosch, Western Cape and KwaZulu-Natal, together with the Council for Scientific and Industrial Research (CSIR), were identified as water centres of excellence in the NEPAD Southern African Network of Centres of Excellence. These centres were also included in the SASSCAL water research themes. All four centres were involved in long-term research in specific locations and were also actively collaborating with international partners.

The SASSCAL water research in South Africa had two domains, both of which were embedded in the idea of continued hydrological research related to long-term monitoring and advances in methodology to better the prospects of being a living laboratory and enhance the prospects of modelling related to the idea of twinning (Flugel, 2012). The two categories were: (1) hydrological and hydro-geological baseline data and modelling, and (2) risk assessment with the possibility of generating early warning information. This research concept was aimed at setting standards for monitoring and mitigating the drought conditions originating from climate change.

The major research locations in South Africa were Cathedral Peak in KwaZulu-Natal Province; the Sandspruit, Verlorenvlei, and Heuningnes catchments in the Western Cape Province; and the Klein-Letaba system in the Limpopo Province. These catchments have been chosen primarily because long-term monitoring of some water components is already taking place and because they are located in climatically different regions of the country. Data on climate, streamflow, and groundwater depths were collected in the catchments.

Miller et al. (2018) studied the complex interaction between recharge rates, salinity, and suitability of use of groundwater in the Verlorenvlei area on the West Coast of South Africa. By using groundwater and weather measuring equipment and applying groundwater modelling, Miller et al. (2018) provided an improved understanding of the interdependence of domestic, agricultural, and ecological water requirements. The improved understanding of hydrology of the West Coast supports planning for the effects of climate change, and the lessons from this work will now be applied beyond this area.

Malan (2016) evaluated the possibility of using geomorphons to produce improved digital geomorphic and soil maps. This approach allows the inclusion of human knowledge in terrain classification, thereby improving the topographic and landscape analysis. This was done through redefining mapped soil properties by making use of elevation models and a process of land form identification and mapping using GIS.

As gully erosion is recognised as a major land degradation process to natural and farmland, especially in the Western Cape Province, Olivier et al. (2018) investigated the current dynamics and impact of gully erosion on agricultural

Figure 5: Fishery structures in the Okavango Delta, Botswana. (Photo: J. Helmschrot, 2015)

systems in the Western Cape. The field-based case study of a classic, discontinuous gully system in the Swartland quantified sediment movement at hillslope scale and related it to rainfall and field observations of gully activity. This showed that the gully system is not only an active sediment source, but also a conduit for sediment from hillslopes. It was further noted that agricultural practices such as ploughed contour banks are causing the expansion of the gully network, in addition to delivering sediment from hillslope sources to the gully system. Vegetation cover was found to reduce gully erosion temporally by up to 91.6%.

Data collection and the enhancement in monitoring were part of a capacity-building programme during the research. The use of field equipment, along with its calibration and long-term maintenance and monitoring, became key activities in the development programme, a feature that also contributes to the idea of living labs. Capacity building in terms of training also formed part of the twinning idea with catchments in the rest of the SASSCAL countries. The South African team is consequently busy building this capacity in the other SASSCAL countries, and this infrastructure will support these activities. It is also important to mention the standardised monitoring infrastructure generated, with the ability to duplicate this in other SASSCAL countries. The key items in capacity building are related to the various methods of groundwater monitoring, flow measurement and monitoring (e.g., distinguishing between surface runoff, subsurface flow, and deep drainage), and climate monitoring.

Botswana

Research in Botswana focused on two aspects of the water tasks: increasing baseline data collection and understanding the complex interaction between natural and human systems with a specific focus on the Okavango Delta and the upper Limpopo.

The Okavango Delta in Botswana is one of the most famous wetland systems in the world and is mostly protected, but land use and population growth around the delta affects water quality (Kolawole et al., 2017). Apart from its ecological importance, the delta is a key source of drinking water (Mogobe et al., 2014). One key challenge in managing the delta is finding a balance between eco-tourism (i.e., environmental protection) and agriculture (i.e., food security) (Kolawole et al., 2017) (Fig. 5). Another challenge is small farmers' varying levels of knowledge regarding sustainable use of fertilisers and access to appropriate products, leading to chemical pollution of the streams flowing to and from the delta (Kolawole et al., 2017).

The SASSCAL research conducted by Mogobe et al. (2018) provided much-needed monitoring equipment and data to better understand the level of water pollution in the Upper Okavango Delta. The study area was in the Okavango Panhandle, the main watercourse that flows into the delta in Botswana, and therefore an important monitoring point. The researchers continuously monitored water quality between 2014 and 2017 using physio-chemical parameters. A positive research outcome of acceptable ionic composition shows that wetland systems have thus far been successful in keeping the delta's water quality at acceptable levels, in spite of the human impact from diversifying land uses in the Upper Okavango Delta.

The Notwane catchment in Botswana is a strategic catchment for water resources in Botswana. Gaborone's water supply is primarily based on water from the Gaborone Dam, which receives its inflow from the Notwane catchment. The continuous water supply to Gaborone and surrounding areas is a concern to water managers, given the variability of rainfall in the catchment and uncontrolled water uptake in tributary areas. It has experienced declining water levels in recent years due to a variety of causes, including the effects of climate variability and change, as well as the impact of more than 300 farm dams located upstream of Gaborone Dam.

Despite these environmental issues, the catchment does not have sufficient hydro-meteorological stations to adequately assist in addressing key water resources issues in the catchment. Utilising innovative modelling and EO-based mapping tools, a modelling study undertaken in the Notwane catchment (Meinhardt et al., 2018) has documented how up-to-date technologies can be used to analyse water level dynamics in the dam in the context of rainfall variability and human activities in the basin.

In support of improving data availability and water management in semi-arid environments with highly variable rainfall conditions, Moalafhi et al. (2018) utilised an experimental set of automated weather stations over Notwane catchment to improve the understanding of the predictive capacity of the monitored variables. The study has shown that observed hydro-climatic time series can be notably improved in quality and length when coupling Artificial Neural Networks (ANNs) with different modelling approaches to describe and validate inherent relationships with precipitation. It is also revealed that simulated precipitation exhibits a similar mean and variability with the observations, despite poor simulations for low and high precipitation events.

Zambia

Water research in Zambia focused on the surface water quality of the upper Zambezi, the resilience of floodplains along the Zambezi River, and the role and economic implications of sedimentation in wetlands and reservoirs in the central and southern parts of Zambia.

Spatial and temporal changes may serve as valuable indicators of the level of change in a wetland system, such as the Barotse Floodplain in the Western Province of Zambia (Zimba et al., 2018). The pressures on this floodplain are particularly high, with more than 80% of the inhabitants owning livestock that graze on the communal lands (Turpie & Barnes, 2003). The Barotse Floodplain is a key economic driver for Zambia, but growing and conflicting uses are threatening the ecosystem's functioning (Turpie & Barnes, 2003). Nyambe et al. (2018), through SASSCAL, set out to determine the seasonal variation in water quality parameters in the Barotse Floodplain, through which inferences could be made into spatio-temporal variation. Water samples were collected across the floodplain and tested for their physical, bacteriological, and chemical characteristics. Sediment samples were tested for their chemical elements. Through the analyses of these samples, the surface water quality and sediments of the Barotse Floodplain were characterised during low and high flows.

The researchers found that the floodplain may play a critical role in being a natural sink of some elements, although a high spatio-temporal variability of parameters was observed. It was concluded that the mechanisms and drivers for the variability and varying loads could be attributed to both anthropogenic and natural processes. Anthropogenic effects resulting from deforestation and increased agricultural production in the surrounding areas of the floodplains led to high sedimentation and high nutrient loading, low dissolved oxygen, and bacteriological contamination of water, especially in settled water courses. Nyambe et al. (2018) expect that future economic pressures in western Zambia due to population growth and limited resource availability may exacerbate these effects. The study further revealed that the observed change in water quality parameters is also related to natural processes, such as low and high flooding patterns. These processes are critical in the 'renewal' of biogeochemical processes and ecological balance of the floodplain. Drawing on their results, the authors emphasise that ensuring proper management of the floodplain is essential to ensure climate change resilience and thereby protect the economic value of this system. The work was supported by modelling studies in the Luanginga catchment, which revealed that a decrease in rainfall and higher temperatures cause lower water quantities, resulting in a reduction of flood extent (35%) and duration and, thus, alteration and damage to the highly productive and valuable wetland ecosystem (Meinhardt et al., 2018). The authors conclude that this will increase risks and vulnerability for the people who depend on the flooding pattern in the wetlands.

A second study focused on mapping and quantifying the extent of sedimentation and erosion in Lusaka and the country's southern provinces. This exercise focused on the storage capacity of small reservoirs and sedimentation from agricultural fields and its impact on both ecosystems and the economy of the agricultural and water sectors at the national level. The aim was to approach rural communities to raise awareness regarding sedimentation and the problems that it creates, and to provide guidance on optimised land and farm dam management. The study provided bathymetric surveys and mapped more than 500 farm dams. This is the most thorough inventory of manmade dams and reservoirs in SADC. The study was supported by case studies, such as one presented by Chomba and Sichingabula (2015), who determined sedimentation rates and their effects on four small reservoirs in the eastern parts of the Lusaka district. The results showed that reservoir capacity storage losses were in two to three orders of magnitude, indicating how serious sedimentation was on small reservoirs. The study called for dam owners to begin regularly dredging the deposited sediment, which will increase storage capacity and ensure sustainable use of the water resources in small reservoirs for local communities. The status of sedimentation on small reservoirs in central Zambia is similar to that in southern parts of the country, as reported by Muchanga (2017). Muchanga et al. (2017) determined concentration levels and the distribution of selected physico-chemical parameters of water in the Makoye Reservoir and their implications for livestock. Their findings indicate that chemical sedimentation might be detrimental to reservoir water quality but may still be useful to domestic animals given that most analysed chemical and physical parameters were found to be within acceptable limits recommended for livestock watering.

Angola

Water research is an evolving discipline in Angola. Given the data scarcity and lack of monitoring infrastructure, the focus is still very much on collecting baseline data and establishing monitoring systems in the country. Three studies were conducted in Angola to support data collection and to strengthen research capacities in hydrological monitoring and assessment.

In the Rio Giraul Basin, an experimental monitoring system was established to observe runoff dynamics and sediment transport during the rainy season—a process that repeatedly causes severe damage to infrastructure. The basin is located in the Province of Namibe, in southwest Angola, and characterises the transition between the high plateau of Chela Mountain, which is approximately 2 300 m above sea level. Here there is a sudden change of height from 2 200 m to 950 m above sea level in only 5 km—from the Tundavala Ridge where the Giraul River (there known as Munhino River) starts, to the mean heights of Bibala. The middle reaches of the river cross the Angolan part of the Namib Desert, defining the arid conditions in large parts of the catchment. The river drains into the Atlantic Ocean near the city of Namibe. The catchment covers an area of about 4 500 km². Given the area's remoteness and difficulties in accessing wider parts of the catchment, the installation and operation of 10 Automatic Weather Stations (AWS), as well as three runoff stations to provide consistent and reliable data, is considered a successful step towards the establishment of the experimental catchment. However, vandalism poses constant challenges. The lack of actual data records was addressed by re-analysing data, including EO-based rainfall information and historical observations. The combined analysis of the available data set led to the conclusion that the upper areas receiving higher rainfall, i.e., 650 mm/year between 1962 and 1972, are well covered by all products, while rainfall for the middle reaches varies between 140 mm and 400 mm/year and in the coastal areas, it ranges between 100 mm and 280 mm/year. This showed the uncertainty in data for this sparsely covered area. Further analysis is needed to better understand atmospheric conditions, which will eventually control the runoff generation mechanisms. Addressing this demand, a process-based, spatially distributed rainfall-runoff model was implemented, providing the basis for model-driven analyses of recent and future hydrological process dynamics.

A second study aimed to contribute to the updating of multiple hazard maps and geological-geophysical risk assessments at the medium and large scales, with a primary focus on the Province of Luanda. Various geophysical and geotechnical surveys utilising refraction seismics, Standard Penetration Tests (SPT), and the Manual Light Dynamic Penetrometer (PDL) Test have enabled researchers to produce updated digital geological maps at scale 1:50 000, as well as various digital diagnosis maps (e.g., topography, lithology, tectonics, hydrological and hydrogeological, land-use maps, etc.) for the Province of Luanda. In addition, geological hazard maps characterising zones of mass movements (e.g., erosion, landslides, and falling of materials) and floods were produced. All data were integrated in the GIS GEOURBE system—a computer platform that allows managing and updating all the geological and geotechnical information for the city of Luanda and its surroundings. The system will be made available to the relevant authorities and the wider public.

Baptista et al. (2018) conducted a study in the eastern provinces of Angola (Lunda Norte and Lunda Sul) where exhaustive mining activities, such as industrial and artisanal diamond exploitation, and other land-use activities take place in order to assess their impact on water resources and the environment. The authors found mining to be a major driver of environmental impact, severely affecting surface water and groundwater quality, but also changing landscape features through deforestation, erosion, and sedimentation dynamics. These practices also affect the area's floral and faunal biodiversity, all leading to environmental changes including altered flow conditions and groundwater recharge mechanisms. The study has shown that replanting of vegetation, the construction of sedimentation basins for capturing mining waste, as well as the creation of waste water treatment facilities may reduce the environmental impact of mining in the region.

Transboundary hydrological assessments and modelling

Using the data gathered and monitoring efforts made in the country-specific studies summarised above, SASSCAL researchers also aimed to develop a comprehensive river basin assessment using further hydrological assessments and modelling. A river basin assessment is an essential part of integrated land and water resources management (ILWRM) in transboundary basins. It is based on an integrated system analysis to identify hydrological process dynamics related to landscape features and socioeconomic development. Interlinked, these components control the regeneration of (sub-) surface water resources and river runoff contribution.

Integrating observed data, assessment and modelling tools, and an advanced understanding of hydrological systems allowed some projects to focus on transboundary basin assessments. Research was conducted on the Gabarone Dam Catchment in Botswana and South Africa; the Okavango Basin in Angola, Namibia, and Zambia; and the Luanginga

Catchment in the upper Zambezi River Catchment in Angola and Zambia. Meinhardt et al. (2018) and Baumberg et al. (2014) used the Integrated Landscape Management System (ILMS) and its hydrological model system, JAMS, to develop the basin assessment and model hydrological process dynamics in these catchments. Because of improved simulation components developed by the research team, the study could more precisely predict the impact of both climate change conditions and human activity (e.g., informal farm dams, contour farming, irrigation agriculture, etc.) on the three catchments. Overall, results of this research showed that climate is the dominant driver of change for runoff generation in the investigated basins. Consequently, management actions need to focus on improved water distribution and water-use efficiency.

The result is a comprehensive database of all information pertinent to the study areas, with information stored in the River Basin Information System (RBIS), which is also part of the ILMS developed at the University of Jena (Germany). The database includes information in the form of time series data, geospatial data, documents, model results, and others, and will serve the purpose of collating inputs for hydrological models in the SASSCAL context. Given the operability of the system, the hydrological database was integrated with the SASSCAL Data and Information Portal (Helmschrot et al., 2018), providing data, models, and model simulations to a wider research community, decision makers such as the Okavango Basin Commission (OKACOM) or the Zambezi River Basin Commission (ZAMCOM), and local and national water authorities in the respective countries.

Another approach targeted the location and severity of droughts at large scale. Droughts are conceptually defined as an extended period of deficit rainfall related to the long-term average condition for a specific region. Using a monitoring period from the year 2000 until 2016, the severity of droughts was assessed for the entire SASSCAL region using vegetation indices as proxies. The results provided insights into spatial patterns of drought severity and, in combination with exposure data (settlements/population), revealed the impacts of drought in the region (Müller et al., 2018).

Conclusion and outlook

This paper summarises the results of 17 SASSCAL research projects that were conducted in the water sector in southern Africa over the past five years. The research was done at a critical time for the southern African nations, as each is experiencing significant drought conditions that have severe social and economic effects. This situation, which is still ongoing in some parts of the SASSCAL countries, highlighted the urgent need for improved knowledge of water resources, as well as improved data for predictive and preventative hydrological modelling, to support the resilience of SADC countries to the effects of climate change. Each research project featured in this section of the SASSCAL research book produced results and findings that governments can use henceforth.

The studies conducted under this SASSCAL research portfolio successfully contributed to the Initiative's mission to produce scientific knowledge products that can inform decision making on climate change in southern Africa. Aiming to improve knowledge on groundwater and surface water and their interaction and to develop more reliable hydrological and hydrogeological data and tools to support (transboundary) water resources management and planning in the region, the presented studies and their outcomes demonstrate that the Initiative's mission has been largely achieved. The goal of notably contributing to and strengthening water research by providing water-related, up-to-date data, information, and knowledge and making these available to stakeholders ranging from academia and decision makers to the wider public across the region has been achieved. Furthermore, some results—particularly those related to modelling—are relevant in an international context beyond the southern African region.

Based on the achieved results, which were presented to the relevant scientific and decision-making communities, SASSCAL has identified gaps in regional water research, particularly in support of ensuring water security in the region. In addressing the identified regional gaps in the water sector, future SASSCAL research activities will build on the achievements of the first phase and place additional focus on:

- improving monitoring capabilities by reviewing and integrating existing networks and, in collaboration with water authorities, automating data restoration and recycling, collection platforms, and stations;
- supporting the development of comprehensive databases through mapping of the nature and extent of both the quantity and quality of surface and underground water resources in the region;
- improving integrated water resource assessments to establish catchment water balance estimations using modelling approaches, spatial and temporal variations in flows and water availability, long-term variations, trends and projections in water availability, and water use and demands, as well as aquifer recharge estimations;
- improving the understanding of surface/subsurface interactions through process-based studies and modelling of changing ecosystems with a strong focus on groundwater recharge mechanisms;
- improving the protection of water resources by assessing the impact of previous and future extreme events (floods and droughts) and urbanisation, conducting vulnerability assessments of water resources to hydrologic extremes, conducting assessments of river flows and aquifer water quality, conducting sediment transport assessments, and identifying and assessing the impact of source and non-source pollutants;
- supporting ecosystems- and catchment-based transboundary water resource management through Transboundary Diagnostic Analysis (TDA) and catchment/basin-wide environmental flow assessments;
- supporting the strengthening of limited regional institutional capacities in

water management and water governance at the national and regional levels; and

- conducting detailed socioeconomic analyses aimed at enhancing the understanding of the inter-linkages between water-based ecosystem services and human well-being to support water authorities in formulating appropriate policies and strategies for poverty alleviation.

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References

Bann, C. & Wood, S.C. (2012) Valuing groundwater: A practical approach for integrating groundwater economic values into decision making—A case study in Namibia, Southern Africa. *Water SA,* **38**(3). *International Conference on Groundwater Special Edition*.

Baumberg, V., Helmschrot, J., Göhmann, H., Steudel, S., Fischer, C. & Flügel, W-A. (2014) Assessing basin heterogeneities for rainfall-runoff modelling of the Okavango River and its transboundary management. *Evolving Water Resources Systems: Understanding, Predicting, and Managing Water–Society Interactions* (ed. by A. Castellarin, S. Ceola, E. Toth, and A. Montanari). Proceedings of ICWRS2014, Bologna, Italy, June 2014. *IAHS*, **364**, 320-325.

Beyer M., Koeniger P., Gaj M., Hamutoko J., Wanke H., & Himmelsbach T. (2016) A deuterium-based labelling technique for the investigation of rooting depths, water uptake dynamics, and unsaturated zone water transport in semiarid environments. *Journal of Hydrology*, **533**, 627–643.

Callaway, J.M. (2004) Adaptation benefits and costs: How important are they in the global policy picture and how can we estimate them? *Global Environmental Change*, **14**, 273–284.

Chomba, I. C. & Sichingabula, H. M. (2015) Sedimentation and its effects on selected small dams east of Lusaka, Zambia. *Modern Environmental Science and Engineering,* **1**, 325–340.

De Clercq, W.P., Jovanovic, N. & Fey, M.V. (2010) Land use impacts on salinity in Berg River water. *Water Research Commission Report nr 1503/01/10.*

Ferreira-Baptista, L., Aguiar, P.F., Pereira, M.J. & Manuel, J. (2018) Impact of mining on the environment and water resources in northeastern Angola. This volume.

Flügel, W.A. (2011). Twinning European and South Asian river basins to enhance capacity and implement adaptive integrated water resources management approaches–results from the EC-project BRAHMATWINN. *Advances in Science and Research*, **7**, 1–9.

Gaj M., Beyer M., Koeniger P., Wanke H., Hamutoko J., & Himmelsbach, T. (2016) In-situ unsaturated zone stable water isotope (2H and 18O) measurements in semi-arid environments using tunable off-axis integrated cavity output spectroscopy. *Hydrology and Earth System Sciences*, **20**, 715–731.

Helmschrot, J., Thompson, S., Kralisch, S, & Zander, F. (2018) The SASSCAL Data and Information Portal. This volume.

Himmelsbach, T. Beyer, Wallner, M. Grünberg, I. & Houben, G. (2018) Deep, semi-fossil aquifers in southern Africa: A synthesis of hydrogeological investigations in northern Namibia. This volume.

Hughes, D.A. (2007) South African research in the hydrological sciences: 2003-2006. *South African Journal of Science*, **103**, 415–418.

IPCC. (2007) Summary for policymakers. Climate change 2007: The physical science basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller). Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Kolawole, O.D., Mogobe, O. & Magole, L. (2017) Soils, people, and policy: Land resource management conundrum in the Okavango Delta, Botswana. *Journal of Agriculture and Environment for International Development,* **111**(1), 39–61.

Kusangaya, S., Warburton, M.L., Van Garderen, E.A. & Jewitt, G.P.W. (2014) Impacts of climate change on water resources in southern Africa: A review. *Physics and Chemistry of the Earth*, **67–69**, 47–54.

Lahnsteiner, J. & Lempert, G. (2007) Water management in Windhoek, Namibia. *Water Science & Technology*, **55**, 441–448.

Luetkemeier, R. & Liehr, S. (2018) Drought sensitivity in the Cuvelai Basin: Empirical analysis of seasonal water and food consumption patterns. This volume.

Luetkemeier, R., Stein, L., Drees, L. & Liehr, S. (2017) Blended Drought Index: Integrated drought hazard assessment in the Cuvelai Basin. *Climate* **5**, 51.

MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.E.O. & Taylor, R.G. (2012) Quantitative maps of groundwater resources in Africa. *Environmental Resources Letters*, 024009.

Malan, G.J. (2016) Investigating the suitability of land type information for hydrological modelling in the mountain regions of Hessequa, South Africa. *MSc thesis.* Stellenbosch University, Stellenbosch.

Meinhardt, M., Fleischer, M., Fink, M., Kralisch, S., Kenabatho, P., De Clercq, W., Zimba, H., Phiri, W., & Helmschrot, J. (2018) Semi-arid catchments under change: Adapted hydrological models to simulate the influence of climate change and human activities on rainfall-runoff processes in southern Africa. This volume.

Miller, J.A., Watson, A.P., Fleischer, M., Eilers, A., Sigidi, N.T., Van Gend, J., Van Rooyen, J., Clarke, C.E. & De Clercq, W.P. (2018) Groundwater quality, quantity, and recharge estimation on the west coast of South Africa. This volume.

Moalafhi, D.B., Kenabatho, P.K., Parida, B.P. & Matlhodi, B. (2018) Predictability of precipitation using data from newly established automated weather stations over Notwane catchment in Botswana. This volume.

Mogobe, O., Masamba, W.R.L., Mosimanyana, E. & Mosepele, K. (2014) Occurrence of aluminium and beryllium in the Okavango Delta, Botswana: Human health risks. 3rd International Conference: Water resources and wetlands. 8-10 September, 2014 Tulcea (Romania). pp. 270–277.

Mogobe, O., Masamba, W.R.L., Mosimanyana, E. & Mosepele, K. (2018) Monitoring water quality of the Upper Okavango Delta. This volume.

Muchanga, M. (2017) Understanding sedimentation process in the Makoye Reservoir of Southern Zambia. *Journal of Geography and Earth Sciences,* **5**, 77–96.

Muchanga, M., Sichingabula, H.M., Chisola, M. Chomba, I.C., Sikazwe, H. & Kalapula, S. (2017) Concentration levels and distribution of selected physico-chemical parameters in the Makoye Reservoir and their implications on livestock. Unpublished paper presented at ZAWAFE Conference, June 2017.

Müller, I., Hipondoka, M., Winkler, K., Geßner, U., Martinis, S. & Taubenböck, H. (2018) Monitoring flood and drought events – earth observation for multi-scale assessments of water-related hazards and exposed elements. This volume.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J. & Urquhart, P. (2014) Africa. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White), pp. 1199–1265. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Nyambe, I., Chabala, A., Banda, K., Zimba, H. & Phiri, W. (2018) Determinants of spatio-temporal variability of water quality in the Barotse Floodplain, Western Zambia. This volume.

Olivier, G. Helmschrot, J. & de Clercq, W.P. (2018) Are large classical gully systems inactive remnants of the past: A field-based case study investigating sediment movement. This volume.

SADC. (2016) SADC launches a US$2.4 billion appeal to assist millions hit by El Nino-induced drought. *Southern African Development Community*. https://www.sadc.int/news-events/news/sadc-launches-u24-billion-appeal-assist-millions-hit-el-nino-induced-drought/.

Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gaye, C.B., Edmunds, W.M. & Simmers, I. (2006) Global synthesis of groundwater recharge in semi-arid and arid regions. *Hydrological processes*, **20**, 3335–3370.

Schlanger, Z. (2018) This major city could be the first to run out of water. *World Economic Forum.* https://www.weforum.org/agenda/2018/01/this-major-city-may-be-the-first-to-run-out-of-water

Stadler, S., Osenbrück, K., Suckow, A.O., Himmelsbach, T. & Hötzl, H. (2010) Groundwater flow regime, recharge, and regional-scale solute transport in the semi-arid Kalahari of Botswana derived from isotope hydrology and hydrochemistry. *Journal of Hydrology*, **388**(3-4), 291–303.

Stein, R. (2005) Water law in a democratic South Africa: A county case study examining the introduction of a public rights system. *Texas Law Review*, **83**, 2167–2183.

Taubenböck, H., Goseberg, N., Setiadi, N., Lämmel, G., Moder, F., Oczipka, M., Klüpfel, H., Wahl, R., Schlurmann, T., Strunz, G., Birkmann, J., Nagel, K., Siegert, F., Lehmann, F., Dech, S., Gress, A. & Klein, R. (2009) Last-mile preparation for a potential disaster: Interdisciplinary approach towards tsunami early warning and an evacuation information system for the coastal city of Padang, Indonesia. *Natural Hazards & Earth Systems Science*, **9**, 1509–1528.

Taubenböck, H., Müller, I., Geiß, C. & Lütkemeier, R. (2018) Managing Hazards: A conceptual foundation. This volume.

Turpie, J.K. & Barnes, J.I. (2003) Balancing ecology and economics in the multiple use of wetlands on communal lands. Proceedings of the VIIth International Rangelands Congress, Durban, South Africa, 26 July – 1 August 2003. pp. 1932–1941.

Wanke, H., Beyer, M., Hipondoka, M., Hamutoko, J., Gaj, M., Koenigerand, P. & Himmelsbach, T. (2018) The long road to sustainability: Integrated water quality and quantity assessments in the Cuvelai-Etosha Basin, Namibia. This volume.

Zimba, H., Kawawa, B., Chabala, A., Phiri, W., Selsam, P., Meinhardt., M. & Nyambe, I. 2018. Assessment of trends in inundation extent in the Barotse Floodplain, upper Zambezi River Basin: A remote sensing-based approach. *Journal of Hydrology: Regional Studies*, **15**, 149–170.

References [CrossRef]

Bann, C. & Wood, S.C. (2012) Valuing groundwater: A practical approach for integrating groundwater economic values into decision making—A case study in Namibia, Southern Africa. *Water SA*, **38**(3). *International Conference on Groundwater Special Edition*. CrossRef

Baptista, L.F., Aguiar, P.F., Pereira, M.J. & Manuel, J. (2018) Impact of mining on the environment and water resources in northeastern Angola. This volume. CrossRef

Baumberg, V., Helmschrot, J., Göhmann, H., Steudel, S., Fischer, C. & Flügel, W-A. (2014) Assessing basin heterogeneities for rainfall-runoff modelling of the Okavango River and its transboundary management. *Evolving Water Resources Systems: Understanding, Predicting, and Managing Water–Society Interactions* (ed. by A. Castellarin, S. Ceola, E. Toth, and A. Montanari). Proceedings of ICWRS2014, Bologna, Italy, June 2014. *IAHS*, **364**, 320-325. CrossRef

Beyer M., Koeniger P., Gaj M., Hamutoko J., Wanke H., & Himmelsbach T. (2016) A deuterium-based labelling technique for the investigation of rooting depths, water uptake dynamics, and unsaturated zone water transport in semiarid environments. *Journal of Hydrology*, **533**, 627–643. CrossRef

Callaway, J.M. (2004) Adaptation benefits and costs: How important are they in the global policy picture and how can we estimate them? *Global Environmental Change*, **14**, 273–284. CrossRef

Chomba, I. C. & Sichingabula, H. M. (2015) Sedimentation and its effects on selected small dams east of Lusaka, Zambia. *Modern Environmental Science and Engineering*, **1**, 325–340. CrossRef

De Clercq, W.P., Jovanovic, N. & Fey, M.V. (2010) Land use impacts on salinity in Berg River water. *Water Research Commission Report nr 1503/01/10.*

Flügel, W.A. (2011). Twinning European and South Asian river basins to enhance capacity and implement adaptive integrated water resources management approaches–results from the EC-project BRAHMATWINN. *Advances in Science and Research*, **7**, 1–9. CrossRef

Gaj M., Beyer M., Koeniger P., Wanke H., Hamutoko J., & Himmelsbach, T. (2016) In-situ unsaturated zone stable water isotope (2H and 18O) measurements in semi-arid environments using tunable off-axis integrated cavity output spectroscopy. *Hydrology and Earth System Sciences*, **20**, 715–731. CrossRef

Helmschrot, J., Thompson, S., Kralisch, S, & Zander, F. (2018) The SASSCAL Data and Information Portal. This volume. CrossRef

Himmelsbach, T. Beyer, Wallner, M. Grünberg, I. & Houben, G. (2018) Deep, semi-fossil aquifers in southern Africa: A synthesis of hydrogeological investigations in northern Namibia. This volume. CrossRef

Hughes, D.A. (2007) South African research in the hydrological sciences: 2003-2006. *South African Journal of Science*, **103**, 415–418.

IPCC. (2007) Summary for policymakers. Climate change 2007: The physical science basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller). Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Kolawole, O.D., Mogobe, O. & Magole, L. (2017) Soils, people, and policy: Land resource management conundrum in the Okavango Delta, Botswana. *Journal of Agriculture and Environment for International Development*, **111**(1), 39–61.

Kusangaya, S., Warburton, M.L., Van Garderen, E.A. & Jewitt, G.P.W. (2014) Impacts of climate change on water resources in southern Africa: A review. *Physics and Chemistry of the Earth*, **67–69**, 47–54. CrossRef

Lahnsteiner, J. & Lempert, G. (2007) Water management in Windhoek, Namibia. *Water Science & Technology*, **55**, 441–448. CrossRef

Luetkemeier, R. & Liehr, S. (2018) Drought sensitivity in the Cuvelai Basin: Empirical analysis of seasonal water and food consumption patterns. This volume. CrossRef

Luetkemeier, R., Stein, L., Drees, L. & Liehr, S. (2017) Blended Drought Index: Integrated drought hazard assessment in the Cuvelai Basin. *Climate* **5**, 51. CrossRef

MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.E.O. & Taylor, R.G. (2012) Quantitative maps of groundwater resources in Africa. *Environmental Resources Letters*, 024009. CrossRef

Malan, G.J. (2016). Investigating the suitability of land type information for hydrological modelling in the mountain regions of Hessequa, South Africa. *MSc thesis.* Stellenbosch University, Stellenbosch.

Meinhardt, M., Fleischer, M., Fink, M., Kralisch, S., Kenabatho, P., De Clercq, W., Zimba, H., Phiri, W., & Helmschrot, J. (2018) Semi-arid catchments under change: Adapted hydrological models to simulate the influence of climate change and human activities on rainfall-runoff processes in southern Africa. This volume. CrossRef

Miller, J.A., Watson, A.P., Fleischer, M., Eilers, A., Sigidi, N.T., Van Gend, J., Van Rooyen, J., Clarke, C.E. & De Clercq, W.P. (2018) Groundwater quality, quantity, and recharge estimation on the west coast of South Africa. This volume. CrossRef

Moalafhi, D.B., Kenabatho, P.K., Parida, B.P. & Matlhodi, B. (2018) Predictability of precipitation using data from newly established automated weather stations over Notwane catchment in Botswana. This volume. CrossRef

Mogobe, O., Masamba, W.R.L., Mosimanyana, E. & Mosepele, K. (2014) Occurrence of aluminium and beryllium in the Okavango Delta, Botswana: Human health risks. 3rd International Conference: Water resources and wetlands. 8-10 September, 2014 Tulcea (Romania). pp. 270–277.

Mogobe, O., Masamba, W.R.L., Mosimanyana, E. & Mosepele, K. (2018) Monitoring water quality of the Upper Okavango Delta. This volume. CrossRef

Muchanga, M. (2017) Understanding sedimentation process in the Makoye Reservoir of Southern Zambia. *Journal of Geography and Earth Sciences*, **5,** 77–96. CrossRef

Muchanga, M., Sichingabula, H.M., Chisola, M. Chomba, I.C., Sikazwe, H. & Kalapula, S. (2017) Concentration levels and distribution of selected physico-chemical parameters in the Makoye Reservoir and their implications on livestock. Unpublished paper presented at ZAWAFE Conference, June 2017.

Müller, I., Hipondoka, M., Winkler, K., Geßner, U., Martinis, S. & Taubenböck, H. (2018) Monitoring flood and drought events – earth observation for multi-scale assessments of water-related hazards and exposed elements. This volume. CrossRef

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J. & Urquhart, P. (2014) Africa. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White), pp. 1199–1265. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Nyambe, I., Chabala, A., Banda, K., Zimba, H. & Phiri, W. (2018) Determinants of spatio-temporal variability of water quality in the Barotse Floodplain, Western Zambia. This volume. CrossRef

Olivier, G. Helmschrot, J. & de Clercq, W.P. (2018) Are large classical gully systems inactive remnants of the past: A field-based case study investigating sediment movement. This volume. CrossRef

SADC. (2016) SADC launches a US$2.4 billion appeal to assist millions hit by El Nino-induced drought. *Southern African Development Community*. https://www.sadc.int/news-events/news/sadc-launches-u24-billion-appeal-assist-millions-hit-el-nino-induced-drought/.

Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gaye, C.B., Edmunds, W.M. & Simmers, I. (2006) Global synthesis of groundwater recharge in semi-arid and arid regions. *Hydrological processes*, **20**, 3335–3370. CrossRef

Schlanger, Z. (2018) This major city could be the first to run out of water. *World Economic Forum.* https://www.weforum.org/agenda/2018/01/this-major-city-may-be-the-first-to-run-out-of-water

Stadler, S., Osenbrück, K., Suckow, A.O., Himmelsbach, T. & Hötzl, H. (2010) Groundwater flow regime, recharge, and regional-scale solute transport in the semi-arid Kalahari of Botswana derived from isotope hydrology and hydrochemistry. *Journal of Hydrology*, **388**(3-4), 291–303. CrossRef

Stein, R. (2005) Water law in a democratic South Africa: A county case study examining the introduction of a public rights system. *Texas Law Review*, **83**, 2167–2183.

Taubenböck, H., Goseberg, N., Setiadi, N., Lämmel, G., Moder, F., Oczipka, M., Klüpfel, H., Wahl, R., Schlurmann, T., Strunz, G., Birkmann, J., Nagel, K., Siegert, F., Lehmann, F., Dech, S., Gress, A. & Klein, R. (2009) Last-mile preparation for a potential disaster: Interdisciplinary approach towards tsunami early warning and an evacuation information system for the coastal city of Padang, Indonesia. *Natural Hazards & Earth Systems Science*, **9**, 1509–1528. CrossRef

Taubenböck, H., Müller, I., Geiß, C. & Lütkemeier, R. (2018) Managing Hazards: A conceptual foundation. This volume. CrossRef

Turpie, J.K. & Barnes, J.I. (2003) Balancing ecology and economics in the multiple use of wetlands on communal lands. Proceedings of the VIIth International Rangelands Congress, Durban, South Africa, 26 July – 1 August 2003. pp. 1932–1941.

Wanke, H., Beyer, M., Hipondoka, M., Hamutoko, J., Gaj, M., Koenigerand, P. & Himmelsbach, T. (2018) The long road to sustainability: Integrated water quality and quantity assessments in the Cuvelai-Etosha Basin, Namibia. This volume. CrossRef

Zimba, H., Kawawa, B., Chabala, A., Phiri, W., Selsam, P., Meinhardt., M. & Nyambe, I. 2018. Assessment of trends in inundation extent in the Barotse Floodplain, upper Zambezi River Basin: A remote sensing-based approach. *Journal of Hydrology: Regional Studies*, **15**, 149–170. CrossRef

Deep, semi-fossil aquifers in southern Africa: A synthesis of hydrogeological investigations in northern Namibia

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Abstract: Groundwater is a key resource throughout southern Africa. Shallow aquifers are generally easy to access, but are often saline and highly vulnerable to contamination. Deep, semi-fossil groundwater resources are difficult to investigate and explore (e.g., spatial extent, volume of stored water, recharge volume, location) but potentially contain large volumes of water of excellent quality. Within SASSCAL, the opportunity to investigate a newly discovered deep aquifer in northern Namibia opened up. This article provides a summary of key findings emerging from research within SASSCAL and previous investigations. In summary, the main findings of these investigations are as follow:

i) Fresh-water in the deep Ohangwena 2 (KOH-II) aquifer is not of fossil origin (i.e., recent recharge exists).
ii) The recharge area of the KOH-II is located in the foothills of the Angolan highlands.
iii) The volume of recharge is low (less than 1 percent of mean annual precipitation).

Although these findings need to be confirmed by further scientific studies and additional drillings, especially to determine the exact extent of the aquifer system, the lessons learnt from more than three decades of investigations in this area allow the formulation of a new strategic orientation for groundwater prospecting in southern Africa: Rather than carrying out extensive drilling, the exploration strategy should be carried out similarly to the exploration for hydrocarbons, where first the tectonical boundary conditions and the sedimentological features are determined. This requires transboundary coordination and extensive planning, but it is the only way to systematically investigate deep, supraregional aquifer systems.

Resumo: As águas subterrâneas representam um recurso-chave em toda a África Austral. Aquíferos pouco profundos são geralmente fáceis de aceder, mas são muitas vezes salinos e altamente vulneráveis à contaminação. Os recursos de águas subterrâneas profundas e semi-fósseis são dificeis de investigar e explorar (e.x.: extensão espacial, volume de água armazenada, volume de recarga e localização), mas contêm potencialmente grandes volumes de água de excelente qualidade. No contexto do SASSCAL, surgiu a oportunidade de investigar um aquífero recentemente descoberto no Norte da Namíbia. Este artigo fornece uma síntese das descobertas chave provenientes da investigação do SASSCAL, bem como de estudos anteriores. Em resumo, as descobertas principais destes estudos são as seguintes:

i) A água doce no aquífero profundo de Ohangwena 2 (KOH-II) não é de origem fóssil, i.e., existem recargas recentes.
ii) A área de recarga do KOH-II localiza-se no sopé das Terras Altas de Angola.
iii) O volume de recarga é baixo (menos de 1 porcento da precipitação média anual).

Embora estas descobertas necessitem de ser confirmadas por novos estudos científicos e perfurações adicionais, em especial para determinar a extensão exacta do sistema de aquíferos, as lições recolhidas ao longo de mais de três décadas de investigação nesta área permitem a formulação de uma nova orientação estratégica para a exploração das águas subterrâneas no Sul de África: Em vez de se realizarem perfurações extensivas, a estratégia de exploração deverá ser realizada de forma semelhante à da exploração de hidrocarbonetos, onde são primeiro determinadas as condições dos limites tectónicos e as características sedimentológicas. Isto requer coordenação transfronteiriça e planeamento extensivo, porém, é a única forma de investigar sistematicamente sistemas de aquíferos profundos e supra-regionais.

Introduction

Namibia is a country of hydrological extremes. Hyperarid climatic conditions dominate at its coasts and in the desert, while other regions experience devastating floods almost every year. From almost no rainfall in the Namib Desert, annual precipitation increases towards the interior of the country, reaching values of around 600 mmy^{-1}, and even 800–900 mmy^{-1} further north (Fig. 1;

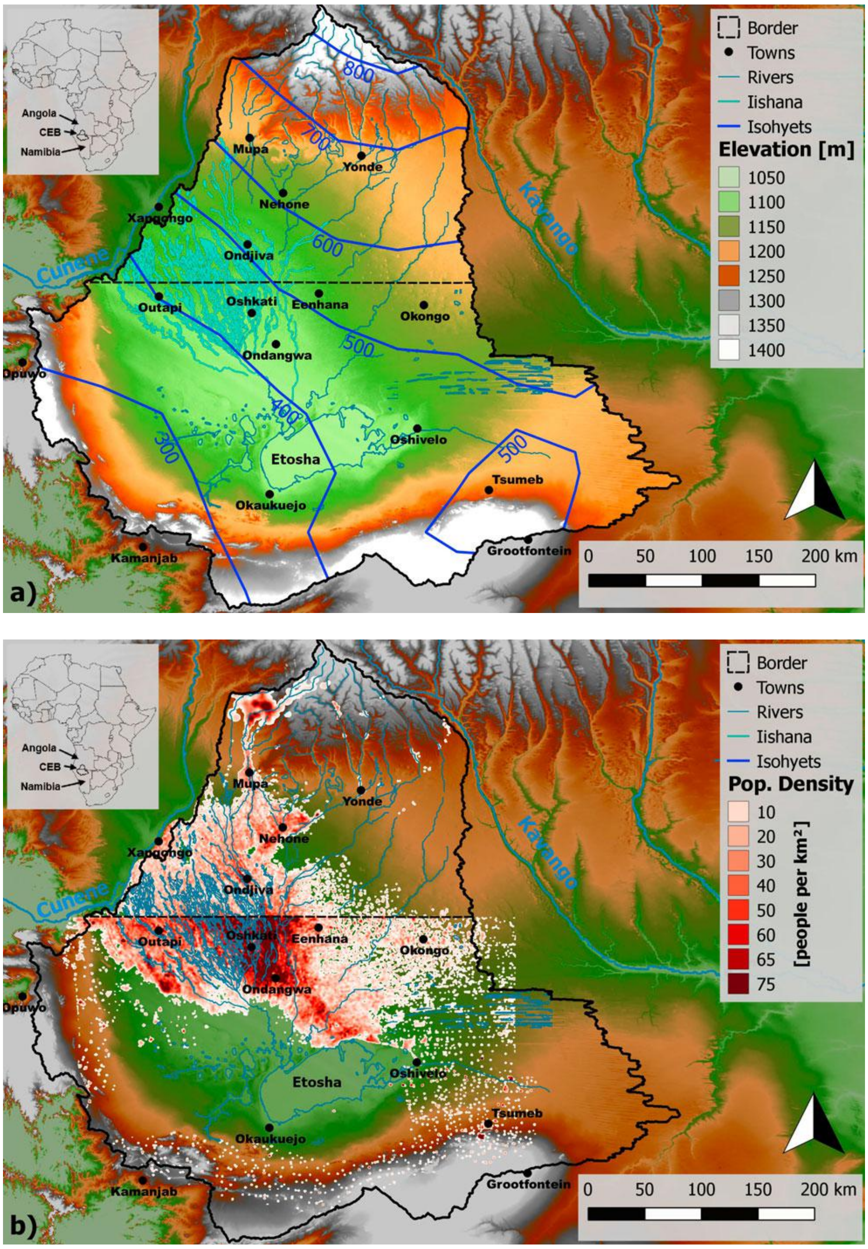

Figure 1: The Cuvelai-Etosha Basin (CEB) and its location within Africa: (a) digital elevation model (DEM) of the CEB, river network, and isohyets; (b) population density (unit: number of people per km²)

Mendelsohn & Weber, 2011). Although these values appear comparable to those of central Europe at first glance, potential evapotranspiration is five to six times higher than rainfall in Namibia because of the higher annual average temperatures and lower relative humidity (Mendelsohn et al., 2013; Mendelsohn & Weber, 2011). A water balance approach would leave little or no remainder for groundwater recharge (Hendrickx et al., 2005). Indeed, the genesis of recharge in such environments is commonly limited to extreme events or flooding, and its amount must be very low (< 5% of annual precipitation; Healy, 2010; Koeniger et al., 2016; MacDonald et al., 2012; Taylor et al., 2012).

In addition, the character of the rainy seasons is highly variable (e.g., with regard to the beginning and end of the rainy season, the number of extreme events), creating an additional challenge for water resources management (Beyer et al., 2016b). The southern winter is characterised by long dry periods lasting several months, during which there is little precipitation (May–October). Spring and summer are the rainy months, with a minor wet season (November–December) and the core rainy season (January–March). In this period, the shallow aquifers are recharged, and most of the rivers show flowing surface water for a few weeks or days. Over a time span of approximately 10 to 15 years, longer periods of aridity and low annual precipitation alternate with wetter, “good” periods (Mendelsohn & Weber, 2011; Mendelsohn et al., 2013). In addition to this periodical behaviour, the year-to-year variability is also vast (Beyer et al., 2016b). The years 1992 and 1993, for instance, were characterised by extreme aridity, which led to a decline in harvests and a loss of livestock (up to one third). On the other hand, repeated periods of extreme precipitation also occur, causing widespread flooding, particularly in the northern parts of the country. This is expected to persist – or even worsen – in the future (e.g., Beyer et al., 2016b). The northern central part of Namibia is home to more than 40% of the Namibian population (Fig. 1) (Mendelsohn et al., 2013; Mendelsohn & Weber, 2011). Strong population growth, which goes hand in hand with increasing urbanisation, a growing agricultural sector, and notable rise in tourism, increases the risk of water shortages.

The Ovambo Basin and its groundwater

The investigated surface water catchment, known as the Cuvelai-Etosha Basin (CEB), is a sedimentary, intracontinental endorheic basin in which the Etosha Pan – with its numerous salt lakes – represents the lowest point. The northern part of the catchment extends over parts of southern Angola up to the Angolan highlands in the southeast (Fig. 1). The subsidence and sedimentation zone of the tectonically formed Owambo Basin (as the basin is commonly known) covers almost the same area as the CEB but extends farther to the east (Fig. 2) (Lindenmaier et al., 2014). The Owambo Basin became part of the larger Kalahari Basin during the Cretaceous with the opening of the South Atlantic. Both the sedimentation and subsidence rates accelerated from the Cretaceous-Tertiary boundary, ultimately giving rise to a sedimentary thickness of almost 400 m to 600 m in the centre of the basin (Miller et al., 2010, Miller 2008).

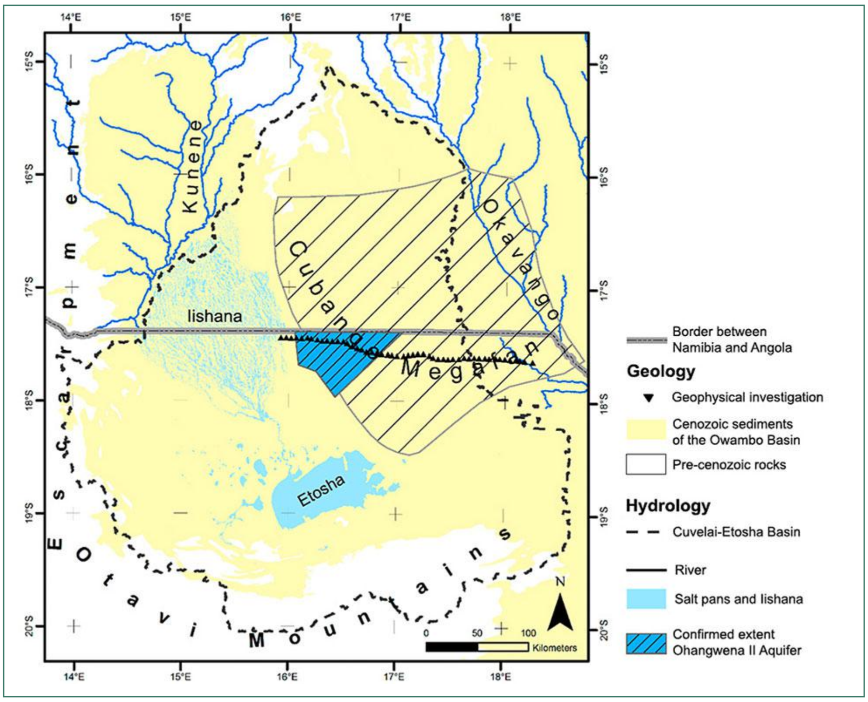

Figure 2: The CEB (surface water catchment) and the Cubango Megafan in Angola and Namibia and the current (confirmed) extent of the Ohangwena 2 (KOH-II) Aquifer.

Whereas shallow groundwater from the perched aquifers (Ohangwena 0, KOH-0) is suitable for drinking in most areas (electrical conductivity [EC] ranges of 52–296 µS/cm), the first continuous upper aquifer (Ohangwena 1, KOH-I) has only limited potential for drinking water (EC ranges of 500–1200 µS/cm) (Hamutoko et al., 2017; Wanke et al., 2018). Salinity is still tolerable in the eastern parts of the CEB, but increases markedly towards the west. In these regions, groundwater is not suitable for drinking, for livestock, or for irrigation of agricultural areas. Water supply has, therefore, for many decades depended on open canals and a dendritic system of small-diameter pipelines supplied from the Caleque Dam in Angola. Despite this water supply scheme, growing demand and the water losses from the existing system, as a result of seepage and evaporation, create a challenge for supplying the population with drinking water.

To find solutions for the ever-increasing pressure on water resources, several groundwater projects in the north of Namibia were undertaken during the last 18 years, with the ultimate discovery of a deep-seated, freshwater-containing aquifer.

Initially an opportunistic discovery, then focus of targeted exploration: A brief history of the Ohangwena 2 (KOH-II) aquifer

Drilling in the Ohangwena region in the northeast of the CEB in the 1970s and 1980s, as part of the governmental water development and drilling programme, rarely went deeper than 100 m. This situation changed, more or less by accident, when drilling an exploration well near Eenyama as part of a government programme to ameliorate the consequences of a drought. The well was drilled beyond the conventional depth of 150 m, down to a total depth of 259 m. After penetrating a sequence of silts and claystone, an aquifer containing freshwater of good quality was encountered below approximately 240 m in depth. Although this well did not reach the base of the aquifer, it quickly became clear that this new, confined aquifer with a pressure level higher than that of the brackish upper aquifer (i.e., subartesian) might represent a valuable new water resource. At this time, however, nothing was known about the geological setting and the hydrological parameters of this aquifer (in particular for the Angolan part), or even its hydrogeological connection to recent or subrecent recharge areas. About a dozen deep monitoring and pumping wells were drilled and two of them were cored. The aquitard separating KOH-I and KOH-II consists of fine sandy and silty sediments with a high clay content. Clay-mineralogical investigations showed that the presence of swelling clay minerals in the pore spaces is responsible for the strong hydraulic sealing effect of the aquitard (Dill et al., 2013). The low permeability was confirmed by hydraulic tests on water-saturated and triaxially pressurised sediment samples (Dill et al., 2013; Lindenmaier et al., 2014). Although the dry core material appeared to be of high porosity, the hydraulic tests carried out under the aforementioned conditions showed that swelling of the clay minerals caused very low hydraulic conductivities on the order of 10^{-9} m s^{-1}. This finding emphasizes the sensitivity of the aquitard with respect to external influences: Such swelling clays are difficult to drill, and therefore have to be penetrated carefully and covered by a strong and continuous casing string. Additionally, the annular space needs to be sealed to prevent flow between the aquifers, especially of brackish water downwards. It is of utmost importance that the pressure level of the deep aquifer must not fall below the bottom of the aquitard during pumping.

The hydraulic pump tests carried out in the aquifer system revealed permeability coefficients on the order of 10^{-6} to 10^{-5} m s^{-1} (Dill et al., 2013). This range corresponds approximately with the permeability deduced from granulometric and hydraulic tests. Because of the thickness of the sediments, combined with the high porosity and relative homogeneity, this aquifer is considered highly productive. An example of a well and sedimentological log from one of the deep drillings from northern Namibia is shown in Figure 3.

The crucial question: Fossil groundwater body or current groundwater recharge?

The key question to be answered with respect to the future use of this new water resource is whether it is a fossil deposit or whether the aquifer receives recent groundwater recharge. Even with low recharge rates, the enormous size of the

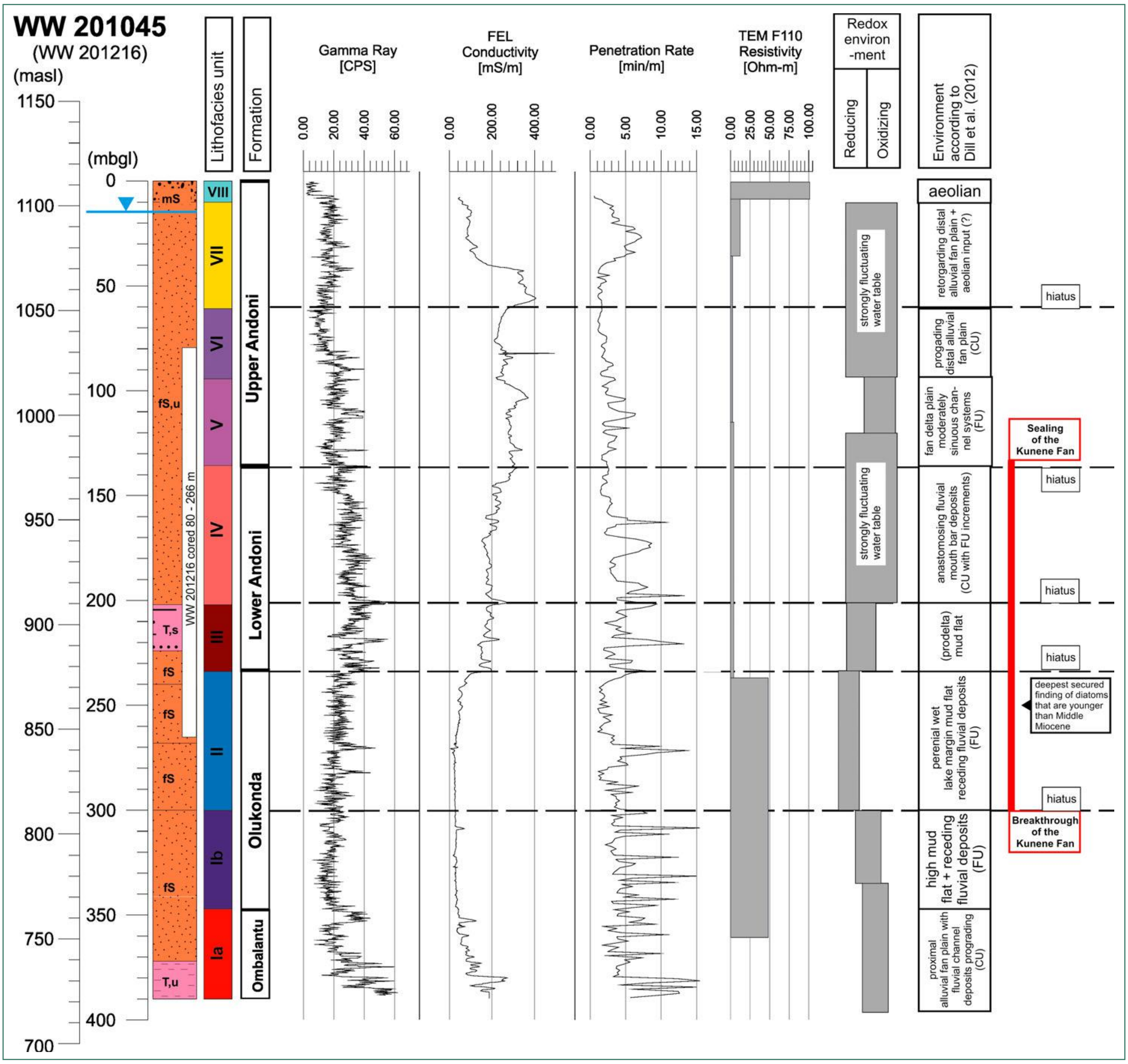

Figure 3: Example of sedimentological and well log as well as geophysical tests from one of the deep drillings in northern Namibia (modified after Lindenmaier et al., 2014)

potential recharge area means that large volumes of water could be involved; hence, knowing the approximate amount of recharge – if existent – might open up an avenue for developing sustainable extraction schemes. If the KOH-II were a fossil aquifer, no sustainable management would be possible in principle. In that case, the new groundwater deposit would have to be seen mainly as a strategic resource for use during extreme droughts. The presence of potential groundwater recharge areas was suspected previously from an initial analysis of satellite images in the neighbouring outcrops of the Angolan highlands. However, only sparse hydrogeological information is available from this area. The Angolan part of the CEB is hardly accessible, even years after the end of the civil war in Angola in 2002, because it has not yet been completely cleared of mines. The part of the Cubango Megafan (Fig. 2) located in this area, as well as the neighbouring Angolan highlands, however, are the key for understanding this transboundary groundwater system.

Within SASSCAL, the opportunity to carry out scientific research on the deep aquifer system emerged. Together with a local partner, the University of Namibia (UNAM), and with the support of the German Aerospace Center (DLR), key questions related to the deep Ohangwena 2 aquifer (KOH-II; Lindenmaier et al., 2014) were investigated:

- Is there recent groundwater recharge, or is the water in KOH-II solely of fossil origin?
- Where does the recharge originate?
- What is the approximate rate of current recharge?

Answering these questions is an essential step to determine the sustainable extraction rate, a prerequisite for sustainable management of groundwater resources.

Methods

Indicators of recent groundwater recharge?

Satellite radar interferometry (InSAR) has been shown previously to be a useful

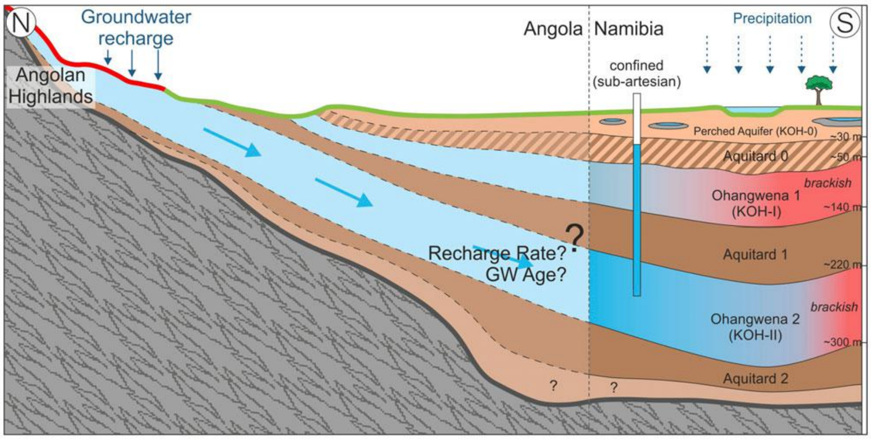

Figure 4: Schematic, vertically exaggerated section of the aquifer system showing the perched aquifer Ohangwena 0 (KOH-0; 0–30 m below surface); brackish Ohangwena 1 (KOH-I; 30–50 m below surface) and the deep, semi-fossil aquifer Ohangwena 2 (KOH-II; ca. 220–300 m below surface (Lindenmaier et al., 2014; Wallner et al., 2017). Also highlighted is the potential recharge area in Angola.

tool for the analysis of ground uplifts and subsidence processes on a regional scale, which can be used to study groundwater recharge or aquifer depletion (i.e., Bell et al., 2008; Ferretti et al., 2014, Hanssen 2001, Lu & Danskin, 2001). Here, we apply the concepts of InSAR to evaluate the possibility of infiltration at the foothills of the Angolan highlands to the outcrops of the KOH-II aquifer (Lindenmaier et al., 2014). The method can – in brief – be described as follows:

A satellite sends radar waves to the land surface and detects the signal reflected by the ground surface (e.g., in 3 m x 3 m pixels).

This procedure is repeated in time intervals (e.g., every two weeks).

The phase difference for each pixel between subsequent overflights is compared between the images. In this way, uplift or subsidence processes at an extremely high resolution can be identified.

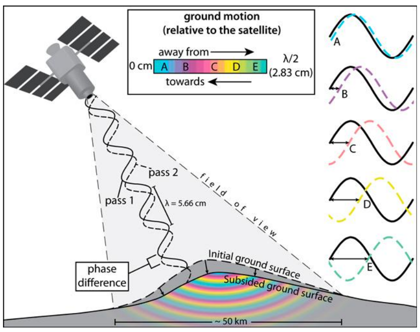

Figure 5: Principles of radar interferometry (InSAR) for the detection of changes in the land surface. [Source: http://volcano.si.edu/volcanoes/region13/hawaii/maunaloa/3705mau2.jpg]

The principle of radar interferometry is depicted in Figure 5.

Within SASSCAL task 010, the DLR provided a strip survey (interval ca. two weeks; temporal coverage between July 2015 and February 2016) using the TerraSAR-X satellite, with a horizontal resolution of 3 m x 3 m and a vertical resolution of a few millimetres. For a pilot area located in the Angolan part of the CEB (Fig. 6), TerraSAR-X data were processed and interpreted as explained above. In addition, the thermal bands of Landsat and MODIS imagery were used for the pilot area (Fig. 6) to detect characteristic features (e.g., wetlands).

Where does current recharge originate? What is the approximate magnitude of current recharge?

The satellite image evaluation formed the basis for the development of a conceptual regional numerical groundwater model (for details of the model set-up, see Wallner et al. (2017). It covers the upper CEB and includes all existing hydrological, hydraulic, sedimentological, and hydrogeological information. Measured groundwater level fluctuations in the KOH-II revealed a seasonal signal, pointing at seasonal groundwater recharge. An initial geological analysis showed that the KOH-II crops out into the foothills of the Angolan highlands. The recharge area has thus to be sought there. However, the exact location and size of the recharge area was unclear. Theoretically,

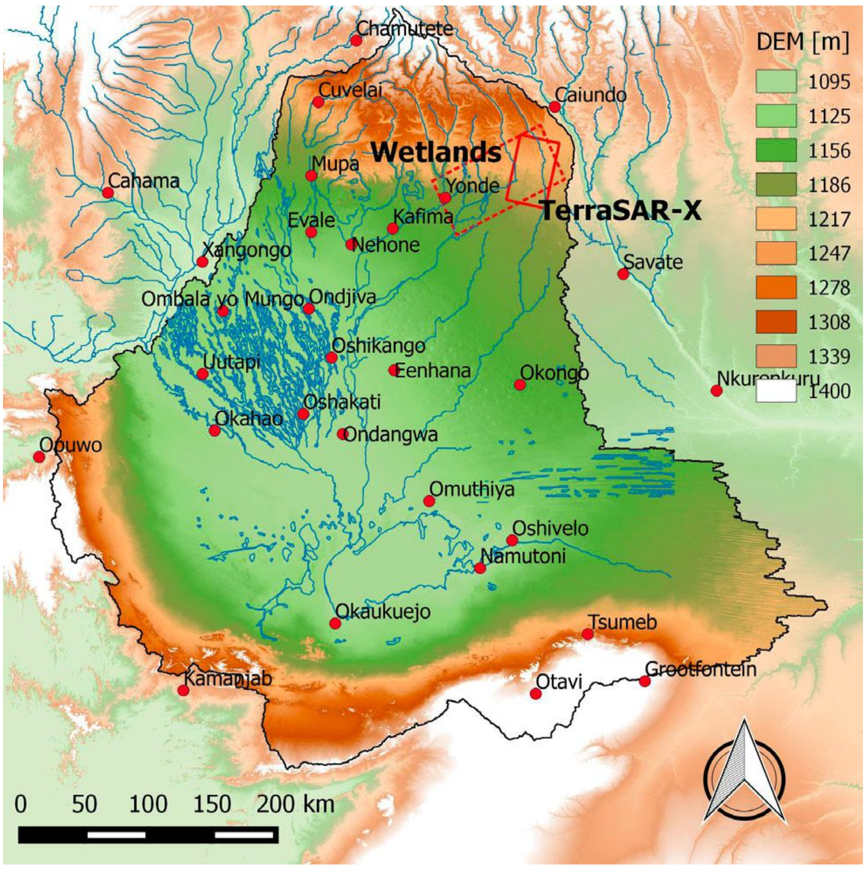

Figure 6: Pilot area chosen for the analysis of vertical ground movement using TerraSAR-X data.

recharge could stem from infiltration at the foothills of the Kunene highlands in the northwest and the Angolan highlands in the north. Potentially, an exfiltration from the Cubango River to the northeast is also possible. Since correct boundary conditions, especially for water inflow, are essential for any model analysis, the boundary conditions had to be identified by modelling itself. In a heuristic modelling approach, a set of 143 physically realistic boundary conditions were defined and implemented in the subsequent calculations. The least-squares measure was used to identify plausible and physically realistic model runs realisations that gave the best match to (a) the groundwater levels measured in the observation wells, (b) the flow direction inferred from the groundwater contour maps, and (c) the age of the groundwater determined using the radiocarbon method (^{14}C). The latter was assigned a lower weighting than the previous two. We refer to Wallner et al. (2017) for a detailed description of methods and data.

Results

The satellite data were employed to evaluate whether seasonal infiltration at the foothills of the Angolan highlands might occur. In Figure 7, the relative changes in the soil surface for the dry season (period of analysis: June 12–September 30, 2015; Fig. 7a) and the rainy season (November 13, 2015–February 20, 2016; Fig. 7b) are shown. During the dry season, a clear subsidence in the northeast of the analyzed strip can be identified. The subsiding area is bounded by a sharp edge (black, dotted line in Fig. 7a), which represents the zone of transition between Quaternary sediments in the centre of the basin to Neogene sediments on the edge of the basin. This area is also located at the foothills of the Angolan highlands (recharge area)—that is, where the surface area becomes flat.

South of this edge, an uplift of up to 10 mm is clearly visible. This uplift is present across different vegetation forms (not shown here; see Mendelsohn et al., 2013; Mendelsohn & Weber, 2011). There are several possible causes for uplift and subsidence. One involves swelling processes of the soil clay minerals, whilst other factors can be attributed to hydromechanical effects in the pore spaces of the aquifer itself. Because no salt crusts or similar features were identified during the dry season in the satellite images of the uplifted areas, and because these areas are wetlands, one can assume that the uplift taking place during the rainy season must be caused by the infiltration and/or transport of water. This confirms the hypothesis that water indeed percolates towards the deeper aquifer layers at the foothills of the Angolan highlands where the deep aquifer crops out (i.e., towards KOH-II). Because Figures 7a and 7b indicate uplift during both the wet and dry seasons, one might interpret that this process is occurring seasonally. However, this hypothesis needs to be investigated further and confirmed by ground-truthing. Currently, the preliminary results from the radar interferometry are complemented

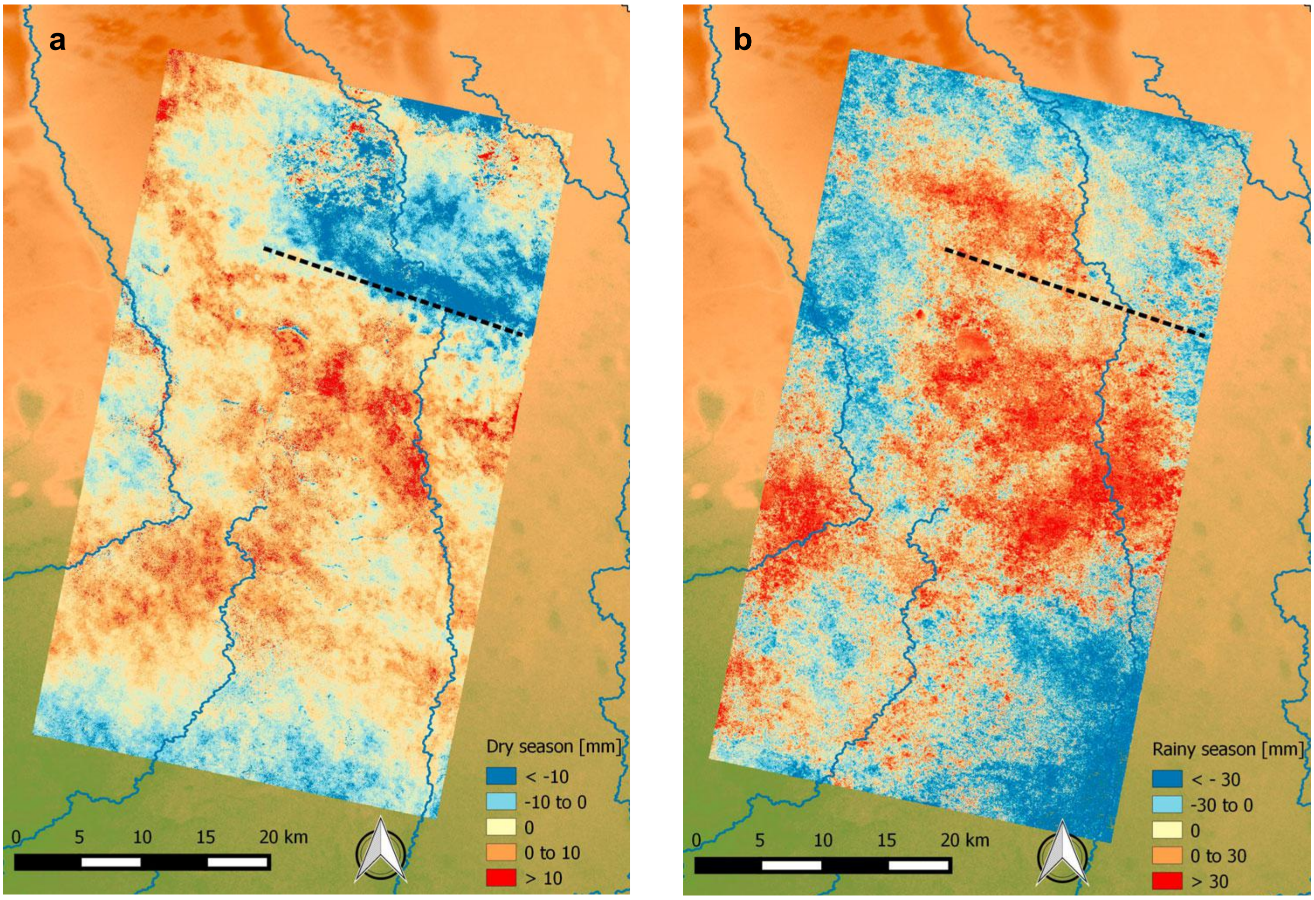

Figure 7: Processed TerraSAR-X images of the surveyed area (CEB, northern Namibia and Angola) (a) during the dry season and (b) during the rainy season. Red colour indicates uplifting, blue stands for subsidence (colour scales are not identical for (a) and (b)).

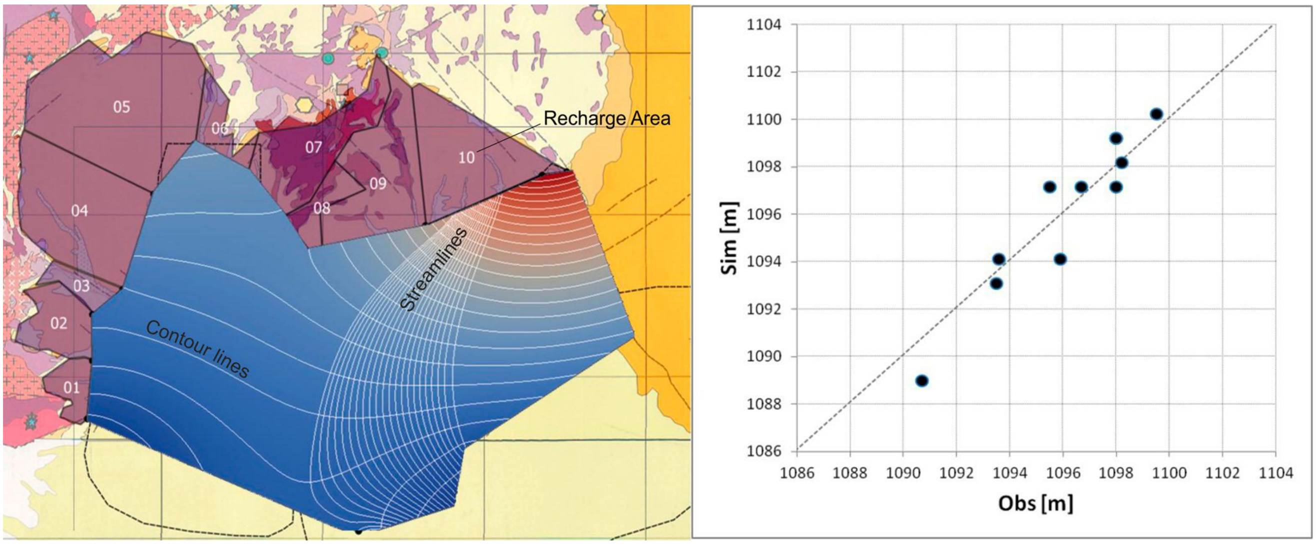

Figure 8: Potential recharge pathways to the Ohangwena 2 aquifer, groundwater contour lines, and streamlines (left); scatterplot of the simulated and observed groundwater levels based on the best realisations of numerical modelling (right) (modified after Wallner et al., 2017).

by an analysis of lineaments and further interpretation of DEMs and other satellite-derived products (e.g., Landsat, MODIS) to improve the confidence in the abovementioned findings.

The numerical flow model showed that recharge comes predominantly from the foothills of the Angolan highlands in the north of the CEB. Infiltrations from the Kunene highlands and from the Cubango River are negligible and small, respectively. Recharge rates constitute less than 1% of total rainfall, yielding recharge volumes of a few million cubic meters per year. This would be the maximum sustainable yield available for extraction. The results of the modelled scenarios, together with the measures for the goodness-of-fit for the best model realisations, are shown in Figure 8. A detailed documentation of the model results can be found in Wallner et al. (2017).

In conclusion, these – even though preliminary – findings suggest that the KOH-II is actively being recharged, but only at very low rates. Based on the numerical models (root mean square error for groundwater levels is 0.82), recharge is less than 1% of the mean annual precipitation. We explicitly state that these results need to be confirmed and reevaluated once an expanded database is available. Further scientific and technical cooperation projects, perhaps under the umbrella of a continuation of SASSCAL, involving the Angolan part of the CEB are urgently needed. Nevertheless, the confidence that recharge from Angola occurs is high based on the presented evidence.

Discussion

From exploration to utilisation

The discovery of the new groundwater resource attracted not only the national but also international media; consequently, hopes and expectations for an improved

Figure 9: Media echo on the discovery of the Ohangwena 2 aquifer.

water supply for the population were great, in particular for rural communities.

The wet years 2009 to 2011 were followed by a severe drought. Many families in the CEB lost more than half of their livestock. This caused the Namibian government to consider making use of water from the new aquifer (personal communication, as of June 2016) even though neither the exact extent nor the amount by which the KOH-II is recharged is sufficiently known. This simple example demonstrates the key role the newly discovered aquifer will play in the future water supply of northern Namibia and which challenges and opportunities it poses for political decision makers in Namibia and Angola. Even though reliable data on the extent and internal structure of the aquifer are currently available for only approximately 20% of the basin and only in northern Namibia, it is clear that a regionally and strategically important groundwater resource has been found. One of the most significant implications of the findings is the importance of protecting this resource. A first step towards this was made in assigning a protected status to the aquifer as part of the country's national planning and legislation processes.

Recently (2013 to 2017), the first wells of the national water utility company have been connected to the pipeline grid and hydraulic tests have been carried out. Additional monitoring efforts in the form of groundwater level loggers are being installed to observe the hydraulic response of the aquifer. At present, only minor abstractions are taken from KOH-II. However, the long-term sustainable use of the aquifer requires the internal dynamics of the aquifer to be recorded and described by improved groundwater models. This must be undertaken in parallel to improving the efficiency of the utilisation and investing in more economical water use. This includes, for instance, reducing leaks to a minimum in the pipeline system and reducing evaporation losses in the open canals.

The numerical modelling results indicated a few millimetres of groundwater recharge per year; currently, between 1 and 3 millimetres per year are assumed (less than 1% of mean annual precipitation). Thanks to the large size of the recharge area, however, enough water could be available to allow the sustainable use of the aquifer for the drinking water supply of the local population, but only if managed very carefully. Using the aquifer to support large-scale irrigation schemes or a long-distance water supply systems (e.g., for the capital, Windhoek) should be considered with a great deal of scepticism. This could overexploit the aquifer and lead to its degradation in the long term.

The discharge area of the newly discovered aquifer remains unclear. Since there are hardly any deep wells in the eastern and sparsely populated Kalahari, one can only speculate. One of the most plausible hypotheses is that the eastern part of the aquifer is an extremely slowly flowing system, which probably leads to a groundwater residence time of 100,000 years or more. This could be addressed only with the help of age dating using radioactive noble gases since ^{14}C analysis is inadequate for this purpose. Contacts have recently been established with the International Atomic Energy Authority (IAEA) in Vienna in this regard, and such investigations could be interesting for a future continuation within SASSCAL. Another hypothesis is that the aquifer is connected to the Graben system in Botswana, which is also characterised by deep and likely fresh aquifers, draining in the direction of the Zambezi to the east. Finally, an artesian relief towards the KOH-I aquifer around the Cuvelai Pan, where artesian wells are common, is possible.

Ways forward

The findings from both SASSCAL and earlier technical cooperation projects are encouraging, but further joint research efforts and confirmation of some of the assumptions are required. Additional numerical models are being prepared based on the established groundwater model. All modelling approaches aim at incorporating the growing amount of information on the structure, and particularly on the initial and general climatic and hydrological conditions. Although the results emerging from two completed PhD projects on groundwater recharge in the CEB (Marcel Gaj and Matthias Beyer) and on the hydrogeochemical characterisation of shallow wells in rural areas (MSc Josefina T. Hamutoko; PhD in preparation) within SASSCAL have meant a great deal of progress, these parameters continue to be the ones with the greatest level of uncertainty.

The recently discovered deep KOH-II aquifer must be considered an opportunistic discovery, and not the result of systematic exploration. It is therefore necessary to adopt a new approach to groundwater development in southern Africa that incorporates a more systematic and intentional approach to investigation. Unlike previous exploration strategies that were based on randomly drilling wells in largely unknown sedimentary sequences with unknown tectonic structures and sedimentary histories, the future exploration strategy for groundwater should pursue the same approach used in oil and gas exploration. Information is first required regarding the tectonic framework, which should be used to derive tectonic structures and boundaries, and the sedimentological background. This information allows us to estimate the hydraulic parameters and, in a final step, to identify potential supraregional aquifers. The fundamental advantage of adopting this kind of approach is not only the ability to save money and avoid drilling expensive dry holes but also to deliver an important source of information for local political decision makers.

Pursuing such an approach assumes that exploration for aquifers of this kind is based on long-term planning and has access to the necessary expertise and data. It is worth repeating that projects of this kind require an interdisciplinary approach, one that SASSCAL has adopted from the beginning. It is therefore essential to incorporate regional geophysical surveys as well as satellite-based remote sensing methods from the start.

The results provide a hopeful sign that the large intercontinental basins in southern Africa may contain more, currently unknown deep aquifers. These new resources should be treated as strategic long-term resources for water supply, however, considering the rapidly growing population. Before any utilisation, sustainable monitoring and management strategies have to be developed. Adaptation to climate change and socioeconomic challenges will be possible only following this approach.

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References

Bell, J.W., Amelung, F., Ferretti, A., Bianchi, M. & Novali, F. (2008) Monitoring aquifer-system response to groundwater pumping and artificial recharge. *First Break,* **26**, 85–91. doi:10.1029/2007WR006152

Beyer, M., Koeniger, P., Gaj, M., Hamutoko, J.T., Wanke, H. & Himmelsbach, T. (2016a) A Deuterium-based labeling technique for the investigation of rooting depths, water uptake dynamics and unsaturated zone water transport in semiarid environments. *Journal of Hydrology*, **533**, 627–643.

Beyer, M., Wallner, M., Bahlmann, L., Thiemig, V., Dietrich, J. & Billib, M. (2016b) Rainfall characteristics and their implications for rain-fed agriculture: a case study in the Upper Zambezi River Basin. *Hydrological Sciences Journal*, **61**, 321–343.

Dill, H.G., Kaufhold, S., Lindenmaier, F., Dohrmann, R., Ludwig, R. & Botz R. (2013) Joint clay-heavy-light mineral analysis: a tool to investigate the hydrographic-hydraulic regime of late Cenozoic deltaic inland fans under changing climatic conditions (Cuvelai-Etosha Basin, Namibia). *International Journal of Earth Sciences*, **102**, 265–304. doi:10.1007/s00531-012-0770-7

Ferretti, A. (2014) *Satellite InSAR data: reservoir monitoring from space*. EAGE Publications, Houten, The Netherlands.

Hamutoko, J.T., Wanke, H., Koeniger, P., Beyer, M. & Gaj, M. (2017) Hydrogeochemical and isotope study of perched aquifers in the Cuvelai-Etosha Basin, Namibia. *Isotopes in Environmental and Health Studies*, **53,** 1–18.

Hanssen, R.F. (2001) *Radar interferometry, data interpretation and error analysis.* Delft University of Technology, Delft, The Netherlands; Kluwer Academic Publishers, Dordrecht.

Healy, R.W. (2010) *Estimating groundwater recharge.* Cambridge University Press, Cambridge, UK.

Hendrickx, J.M.H., Phillips, F.M. & Harrison, J.B.J. (2005) Water flow processes in arid and semi-arid vadose zones. *Understanding water in a dry environment: IAH international contributions to hydrogeology* (ed. by I. Simmers), p. 353. CRC Press, Amsterdam.

Koeniger, P., Gaj, M., Beyer, M. & Himmelsbach, T. (2016) Review on soil water isotope based groundwater recharge estimations. *Hydrological Processes*, **30**, 2817–2834.

Lindenmaier, F., Miller, R., Fenner, J., Christelis, G., Dill, H.G., Himmelsbach, T., Kaufhold, S., Lohe, C., Quinger, M., Schildknecht, F., Symons, G., Walzer, A. & van Wyk, B. (2014) Structure and genesis of the Cubango Megafan in northern Namibia: implications for its hydrogeology. *Hydrogeology Journal*, **22**, 1431–2174.

Lu, Z. & Danskin, W.R. (2001) InSAR analysis of natural recharge to define structure of a ground-water basin, San Bernardino, California. *Geophysical Research Letters*, **28**, 2661–2664. doi:10.1029/2000GL012753

MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.É.Ó. & Taylor, R.G. (2012) Quantitative maps of groundwater resources in Africa. *Environmental Research Letters*, **7**, 24009.

Mendelsohn, J.M., Jarvis, A. & Robertson, T. (2013) *A profile and atlas of the Cuvelai-Etosha basin*. RAISON & Gondwana Collection, Windhoek, Namibia.

Mendelsohn, J.M. & Weber, B. (2011) *The Cuvelai Basin, its water and people in Angola and Namibia*. Development Workshop & RAISON, Windhoek, Namibia.

Miller, R.M., Pickford, M. & Senut, B. (2010) The geology, palaeontology and evolution of the Etosha Pan, Namibia: implications for terminal Kalahari deposition. *South African Journal of Geology*, **113**, 307–334.

Miller, R. (2008) *The geology of Namibia*. 3 vols. Ministry of Mines and Energy, Geological Survey, Windhoek, Namibia.

Taylor, R.G., Todd, M.C., Kongola, L., Maurice, L., Nahozya, E., Sanga, H. & MacDonald, A.M. (2012) Evidence of the dependence of groundwater resources on extreme rainfall in East Africa. *Nature Climate Change*, **3**, 374–378.

Wallner, M., Houben, G., Lohe, C., Quinger, M. & Himmelsbach, T. (2017) Inverse modeling and uncertainty analysis of potential groundwater recharge to the confined semi-fossil Ohangwena II Aquifer, Namibia. *Hydrogeology Journal*, **25**, 1–19.

Wanke, H., Beyer, M., Hipondoka, M., Hamutoko, J., Gaj, M., Koeniger and, P. and Himmelsbach, T. (2018) The long road to sustainability: integrated water quality and quantity assessments in the Cuvelai-Etosha Basin, Namibia. This volume.

References [CrossRef]

Bell, J.W., Amelung, F., Ferretti, A., Bianchi, M. & Novali, F. (2008) Monitoring aquifer-system response to groundwater pumping and artificial recharge. *First Break*, **26**, 85–91. CrossRef

Beyer, M., Koeniger, P., Gaj, M., Hamutoko, J.T., Wanke, H. & Himmelsbach, T. (2016a) A Deuterium-based labeling technique for the investigation of rooting depths, water uptake dynamics and unsaturated zone water transport in semiarid environments. *Journal of Hydrology*, **533**, 627–643. CrossRef

Beyer, M., Wallner, M., Bahlmann, L., Thiemig, V., Dietrich, J. & Billib, M. (2016b) Rainfall characteristics and their implications for rain-fed agriculture: a case study in the Upper Zambezi River Basin. *Hydrological Sciences Journal*, **61**, 321–343. CrossRef

Dill, H.G., Kaufhold, S., Lindenmaier, F., Dohrmann, R., Ludwig, R. & Botz R. (2013) Joint clay-heavy-light mineral analysis: a tool to investigate the hydrographic-hydraulic regime of late Cenozoic deltaic inland fans under changing climatic conditions (Cuvelai-Etosha Basin, Namibia). *International Journal of Earth Sciences*, **102**, 265–304. CrossRef

Ferretti, A. (2014) *Satellite InSAR data: reservoir monitoring from space*. EAGE Publications, Houten, The Netherlands.

Hamutoko, J.T., Wanke, H., Koeniger, P., Beyer, M. & Gaj, M. (2017) Hydrogeochemical and isotope study of perched aquifers in the Cuvelai-Etosha Basin, Namibia. *Isotopes in Environmental and Health Studies*, **53,** 1–18. CrossRef

Hanssen, R.F. (2001) *Radar interferometry, data interpretation and error analysis.* Delft University of Technology, Delft, The Netherlands; Kluwer Academic Publishers, Dordrecht.

Healy, R.W. (2010) *Estimating groundwater recharge.* Cambridge University Press, Cambridge, UK. CrossRef

Hendrickx, J.M.H., Phillips, F.M. & Harrison, J.B.J. (2005) Water flow processes in arid and semi-arid vadose zones. *Understanding water in a dry environment: IAH international contributions to hydrogeology* (ed. by I. Simmers), p. 353. CRC Press, Amsterdam.

Koeniger, P., Gaj, M., Beyer, M. & Himmelsbach, T. (2016) Review on soil water isotope based groundwater recharge estimations. *Hydrological Processes*, **30**, 2817–2834. CrossRef

Lindenmaier, F., Miller, R., Fenner, J., Christelis, G., Dill, H.G., Himmelsbach, T., Kaufhold, S., Lohe, C., Quinger, M., Schildknecht, F., Symons, G., Walzer, A. & van Wyk, B. (2014) Structure and genesis of the Cubango Megafan in northern Namibia: implications for its hydrogeology. *Hydrogeology Journal*, **22**, 1431–2174. CrossRef

Lu, Z. & Danskin, W.R. (2001) InSAR analysis of natural recharge to define structure of a ground-water basin, San Bernardino, California. *Geophysical Research Letters*, **28**, 2661–2664. CrossRef

MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.É.Ó. & Taylor, R.G. (2012) Quantitative maps of groundwater resources in Africa. *Environmental Research Letters*, **7**, 24009. CrossRef

Mendelsohn, J.M., Jarvis, A. & Robertson, T. (2013) *A profile and atlas of the Cuvelai-Etosha basin*. RAISON & Gondwana Collection, Windhoek, Namibia.

Mendelsohn, J.M. & Weber, B. (2011) *The Cuvelai Basin, its water and people in Angola and Namibia*. Development Workshop & RAISON, Windhoek, Namibia.

Miller, R.M., Pickford, M. & Senut, B. (2010) The geology, palaeontology and evolution of the Etosha Pan, Namibia: implications for terminal Kalahari deposition. *South African Journal of Geology*, **113**, 307–334. CrossRef

Miller, R. (2008) *The geology of Namibia*. 3 vols. Ministry of Mines and Energy, Geological Survey, Windhoek, Namibia.

Taylor, R.G., Todd, M.C., Kongola, L., Maurice, L., Nahozya, E., Sanga, H. & MacDonald, A.M. (2012) Evidence of the dependence of groundwater resources on extreme rainfall in East Africa. *Nature Climate Change*, **3**, 374–378. CrossRef

Wallner, M., Houben, G., Lohe, C., Quinger, M. & Himmelsbach, T. (2017) Inverse modeling and uncertainty analysis of potential groundwater recharge to the confined semi-fossil Ohangwena II Aquifer, Namibia. *Hydrogeology Journal*, **25**, 1–19. CrossRef

Wanke, H., Beyer, M., Hipondoka, M., Hamutoko, J., Gaj, M., Koeniger and, P. and Himmelsbach, T. (2018) The long road to sustainability: integrated water quality and quantity assessments in the Cuvelai-Etosha Basin, Namibia. This volume. CrossRef

The long road to sustainability: integrated water quality and quantity assessments in the Cuvelai-Etosha Basin, Namibia

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Abstract: Many arid and semi-arid regions of Southern Africa experience pressure on water resources as a result of limited rainfall, droughts, high population growth, and poor infrastructure. To satisfy domestic, agricultural, and livestock demands, multiple water sources are used, but the scientific and local knowledge on both the quality and quantity of these is limited for the study area. As part of SASSCAL Tasks 007, 010 and 014, numerous field campaigns (2013–2017) were carried out in the transboundary Cuvelai-Etosha Basin (CEB) with the aim of providing a comprehensive description of surface and groundwater resources.

The investigations reveal that sound management and coordinated use of water resources in the CEB need to be introduced. This could include, for example, adding further responsibilities to water point committees and developing management strategies based on a thorough understanding of hydrologically relevant processes. Sufficient water exists, but its quality and quantity are highly variable. Simple actions at a local scale (e.g., rainwater harvesting, fencing off wells, use of perched aquifers) could improve the situation substantially.

Resumo: Muitas regiões áridas e semi-áridas da África Austral sofrem pressão sobre os recursos hídricos, devido à precipitação limitada, às secas, ao elevado crescimento populacional e às infraestruturas precárias. De modo a satisfazer as necessidades domésticas, agrícolas e pecuárias, são utilizadas múltiplas fontes de água, mas o conhecimento científico e local sobre tanto a qualidade como a quantidade das mesmas é limitado para a área de estudo. Inseridas nas Tarefas 007, 010 e 014 do SASSCAL, foram realizadas várias campanhas de campo (2013-2017) na Bacia Cuvelai-Etosha (CEB) transfronteiriça, com o objectivo de oferecer uma descrição detalhada dos recursos hídricos superfíciais e subterrâneos.

As investigações revelam ser necessário introduzir uma gestão sólida e uma utilização coordenada dos recursos hídricos na CEB. Isto poderia incluir, por exemplo, a adição de responsabilidades aos comités das fontes de água, bem como estratégias de gestão de base baseadas num conhecimento profundo dos processos hidrologicamente relevantes. Existe água suficiente, mas a sua qualidade e quantidade são altamente variáveis. Simples acções a uma escala local, como, por exemplo, colher água da chuva, vedar poços e utilizar água de lençóis suspensos, poderão ajudar a melhorar substancialmente a situação.

Introduction

Water scarcity is nothing new to the people in arid and semi-arid regions of Southern Africa. For centuries, they have learned to cope with erratic and limited rainfall, droughts, and dry wells. Human adaptability has its limits, however, and these seem to have been reached and exceeded in some places. The pressure on water resources is higher than ever before. Some rural communities are facing particularly severe difficulties managing their water resources sustainably thanks to a growing population, changing climate, or the wish for better standards of living.

An excellent example is the Cuvelai-Etosha Basin (CEB; Fig. 1), a transboundary river basin shared almost equally by Angola in the north and Namibia in the south, which is home to approximately 40% of the Namibian population. A detailed description of the study area is given in Beyer et al. (2018).

For sustainable management of groundwater resources – whether taken from shallow, hand-dug wells or pumped from deep aquifers – not only the quality of the water but also the pathways (e.g., direct infiltration of rainfall or indirect through lakes or rivers) and the amount by which the aquifer is recharged (groundwater recharge) need to be known. In the highly heterogeneous CEB, with its complex geological history and structure (Lindenmaier et al., 2014; Miller et al., 2010),

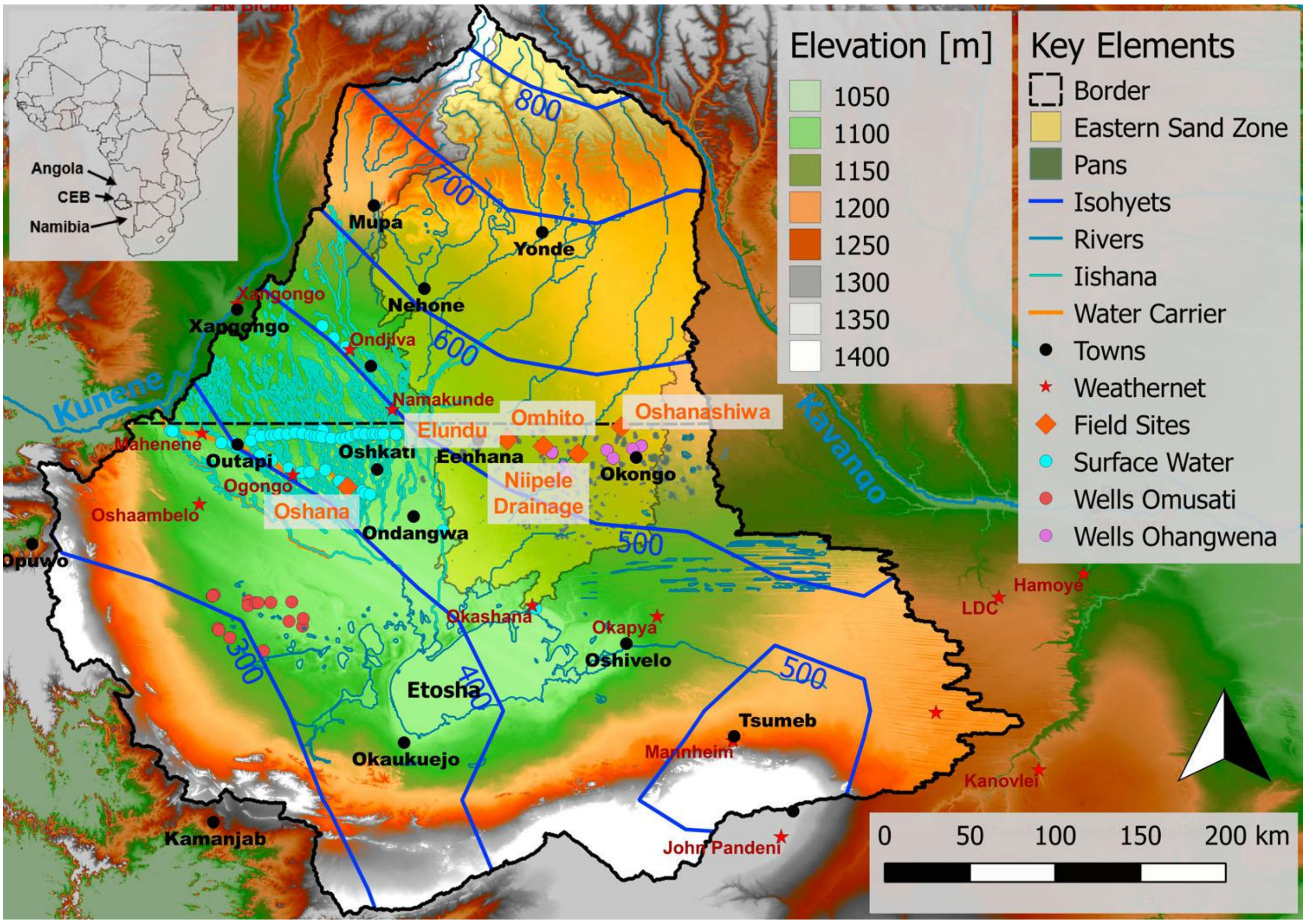


Figure 1: The Cuvelai-Etosha Basin (CEB). The figure shows a digital elevation model (SRTM) of the CEB, isohyets, and important hydrological features of the basin. Furthermore, the investigated sites for surface (turquoise circles) and groundwater (purple circles – Ohangwena Region; red circles – Omusati Region) sampling and recharge estimations (orange diamonds) are depicted. The yellow highlighted area represents the Eastern Sand Zone.

groundwater recharge–related processes are currently not well understood. In addition, there are a number of distinctive landforms present throughout the basin (e.g., *iishana*, *pans*, ephemeral riverbeds, deep Kalahari sands, shallow soils underlain by calcrete), which adds another dimension to an already complicated issue.

It is therefore the aim of this study to provide a comprehensive description of water resources in the Namibian part of the CEB. In particular, the goals are to (1) examine the quantity and quality of surface water, using the 2017 flooding events as proxy; (2) characterize

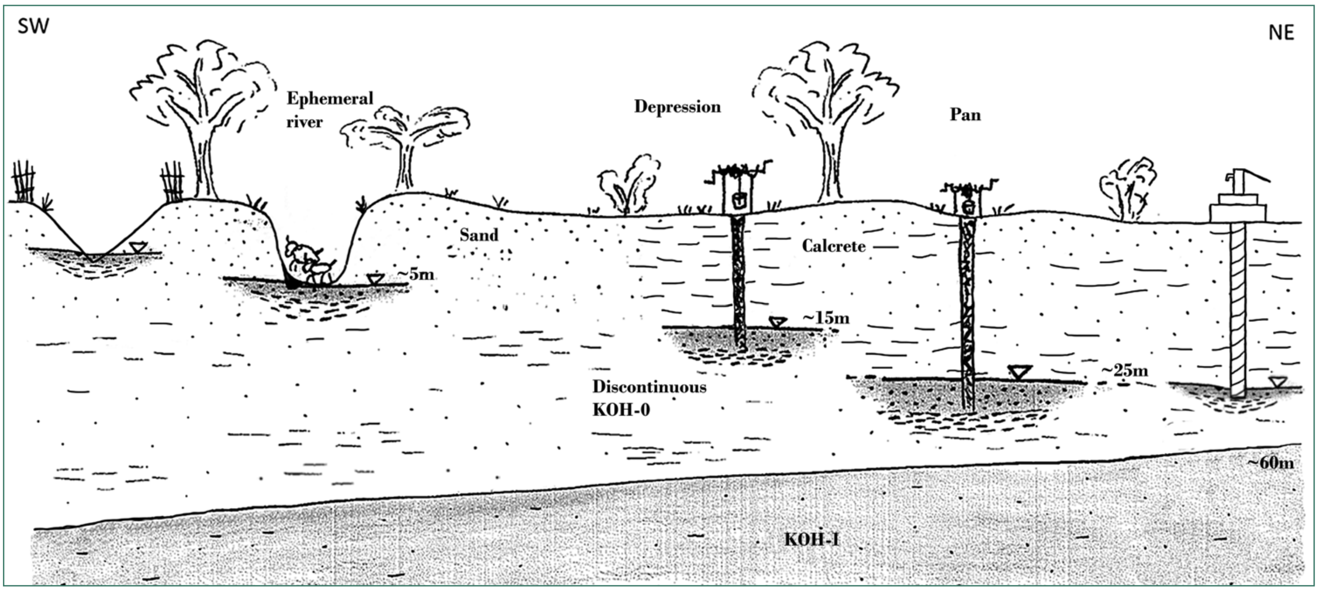


Figure 2: Schematic and vertically exaggerated view of the groundwater storeys in the study area. The graphic shows the perched aquifer Ohangwena-0 (KOH-0; 0–20 m below surface) and the regional aquifer Ohangwena-1 (KOH-1) below.

the quantity and quality of groundwater in shallow aquifers (i.e., KOH-0 and KOH-1; refer to Fig. 2); and (3) investigate recharge mechanisms and quantify groundwater recharge rates of different landforms present within the CEB.

Methods

The 2016/17 rainfall data were collected from five SASSCAL weather stations (SASSCAL Weathernet, http://www.sasscalweathernet.org/index.php) located within the basin. Fieldwork in the basin during the 2016/17 rainy season was carried out at three intervals – namely, in February at the onset of the core rainy season (60 samples), during the peak of the flood in mid-March (42 samples), and during the post-flooding stage at the beginning of April (36 samples). Sampling in both February and March included the upstream section (in Angola) of the CEB. As a result, only 22 water bodies on the Namibian side were sampled in all three field visits to permit a constant, site-specific temporal profiling. Measured parameters included flow velocity using an OTT C20 current meter with an OTT Z400 signal counter set and an impeller mounted on a 20 mm diameter steel rod; the same rod, marked with a ruler, was used to measure water depth. Turbidity (in FAU), pH, and electrical conductivity (EC) were measured onsite using Hach portable instruments. Water samples were collected for isotope measurement and analysed using a laser spectrometer (Los Gatos Research Inc., LGR DLT 100) at the University of Namibia.

To determine the quality of the shallow/local groundwater, samples were collected from 50 hand-dug wells (originating from shallow and deep hand-dug wells in small, circumscribed areas in the Ohangwena and Omusati regions, respectively; refer to Fig. 1). Ten sampling campaigns were carried out between November 2013 and May 2017, usually in the months of March (rainy season), June (early part of the dry season), August/September (peak of the dry season), and November (start of the rainy season). In the field, physico-chemical parameters – namely, pH, electrical conductivity, turbidity (in NTU), oxidation-reduction potential, oxygen content and temperature – were measured with Hach portable instruments. Samples for the determination of cations and anions were taken from each well, and the analyses were performed by Analytical Laboratory Services in Windhoek, Namibia, and at the hydrochemistry laboratory of the Federal Institute for Geosciences and Natural Resources in Hanover, Germany. The reliability of the analyses was checked by calculating the ion charge balance error on all samples. Quality was subsequently assessed using World Health Organization (WHO, 2011) guidelines.

Four independent methods for estimating groundwater recharge through the unsaturated zone were applied and improved within SASSCAL:

- The well-documented chloride mass balance (e.g., Gaye & Edmunds, 1996; Huang et al., 2017; Scanlon, 1991) as a reference method for estimating mean recharge: This method uses the relationship between chloride entering the system (through precipitation and dry deposition) and chloride in the deep unsaturated zone or groundwater to infer recharge.
- The peak-shift method using deuterium as an artificial tracer (e.g., Beyer et al., 2015; Blume et al., 1967; Saxena, 1984; Zimmermann et al., 1966): A tracer (in the present case, deuterated water, ^2H_2O) is artificially inserted into the soil and its downward displacement monitored over time. Recharge is then estimated by combining the information of water content with the distance of displacement over time (e.g., one rainy season).
- An empirical method based on soil water isotope depth profiles (e.g., Allison et al., 1984; Barnes & Allison, 1988; Gaj et al., 2016): When plotting soil water isotopes of the deep unsaturated zone in sandy areas and groundwater isotopes in dual-isotope space, a parallel shift of the former is often observed. The degree of this displacement can be used to obtain a crude estimate of recharge (Allison, 1988; Barnes & Allison, 1988).
- Groundwater level fluctuations from six shallow boreholes drilled in Ohangwena at the villages of Omboloka (2 sites, 23 and 20 m deep), Ohameva (26 m deep), Okamanya (31 m deep), Epumbalondjaba (10 m deep) and Oshanashiwa (30 m deep) (indicated in Fig. 1 as part of Wells Ohangwena) and equipped with Solinst Leveloggers: Water level fluctuations were recorded daily during the 2016/17 rainy season and measured with a water level meter in October 2016 and May 2017. Recharge rates for this specific year were obtained by multiplying the increase in water level with effective porosities obtained during a vulnerability study by Hamutoko et al. (2016). The resulting recharge value is to be seen as a conservative estimate, as water withdrawal was not considered in this simple approach.

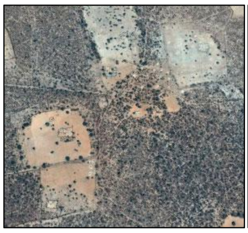
All of these methods require extensive fieldwork and deliver a point estimate of recharge. Therefore, several sites with distinct characteristics (geology, morphology, soil type, and vegetation) were chosen in order to identify landforms comprising potential recharge areas for the near-surface aquifer KOH-0. The selected landforms are summarized in Tab. 1, together with a brief description (also refer to Mendelsohn et al., 2013; Mendelsohn & Weber, 2011). For comparing these point estimates with large-scale approximations of groundwater-storage changes, a remote-sensing approach using GRACE gravity field satellite data was applied (Chen et al., 2016; Longuevergne et al., 2013; Rodell et al., 2007; Yeh et al., 2006). Recharge pathways to the deep KOH-2 aquifer were investigated by means of a groundwater model (Wallner et al., 2017) but are not the focus of this research (we refer to Himmelsbach et al., 2018).

Results

Rainfall and discharge

To characterize the discharge in relation to precipitation amount, corresponding 2016/17 monthly rainfall data from five SASSCAL weather stations situated within the alluvial plains are presented in Fig. 3. Although Mahenene station is

Table 1: Main landforms and representative sites investigated in this study.

Landform / Site	Characterization	Image
Deep sheet sands of the Eastern Sand Zone / *Elundu Forest*, *Omhito, Omboloka 1*	Characteristic landform of the Eastern Sand Zone. The unsaturated zone is dominated by sand covered by a medium-dense forest. The perched aquifer is not present here. Major (potentially deep-rooting) tree and shrub species are *Baikiea plurijuga, Acacia erioloba, Collinum combretum, Salacia luebertii, Terminalia sericea,* and *Colophospermum mopane.*	  
Dune sands and local depressions underlain by calcrete / *Oshanashiwa, Okamanya, Omboloka*	Alternating reddish sand dunes and depressions, found mainly in the Okongo region. Underlain by a thick (up to 20 m) of calcrete. Often, perched aquifers are present in this region. Vegetation is less high because of the calcrete. Depressions are often covered by hand-dug well fields.	 
Iishana / *Oshana Oshakati*	Old river channels. Flooded in the rainy season, creating an interconnected channel system in years with significant flooding. Swellable clay minerals, highly saline. Very low permeability. Grasses in the rainy season; otherwise only Makalani Palms present.	 
Pans / *Deflation Pan Elundu*	Local pans which are present throughout the Eastern Sand Zone. Winds have blown out fine material from the pans that was deposited on the leeward side, creating favourable conditions for farming. The pan itself is filled during the rainy season and used for livestock watering. Mainly carbonate-rich sands, silt, and clay fractions. Low permeability.	 
Ephemeral riverbeds / *Niipele Drainage, Epumbalondjaba*	Remainders of an old river system. Can carry surface water in years with high rainfall. In dry years and during the dry season, water is flowing below the soil surface. Coarse sand of high permeability. The filled-up river channels decrease evaporation. Often hand-dug wells near the riverbeds.	 

missing data from March 9, 2017, onwards, western Cuvelai received comparatively higher rainfall than central Cuvelai. Ogongo, in central Cuvelai, received the lowest amount, with 372 mm (17% below the long-term average of approximately 450 mm y^{-1}) for the entire season. Rainfall at Ondjiva was 24% below the long-term average of approximately 600 mm y^{-1}. All other stations received rainfall above or around their respective long-term averages. Except at Oshaambela, where rainfall

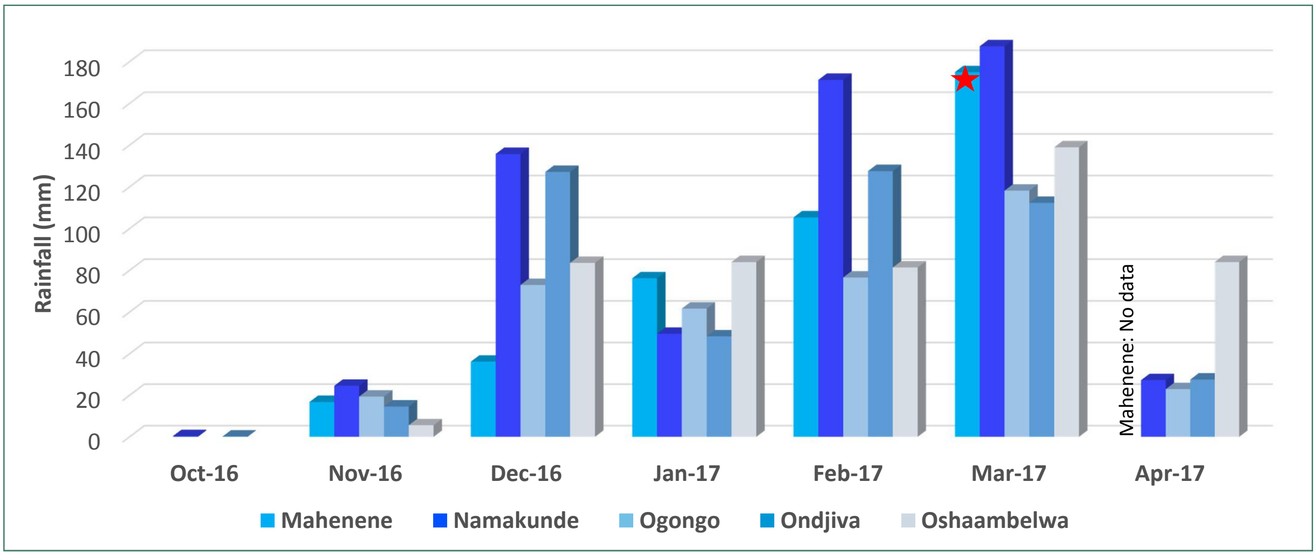


Figure 3: Distribution of rainfall for the 2016/17 rainy season. The star denotes missing data for Mahenene from March 9, 2017, onwards.

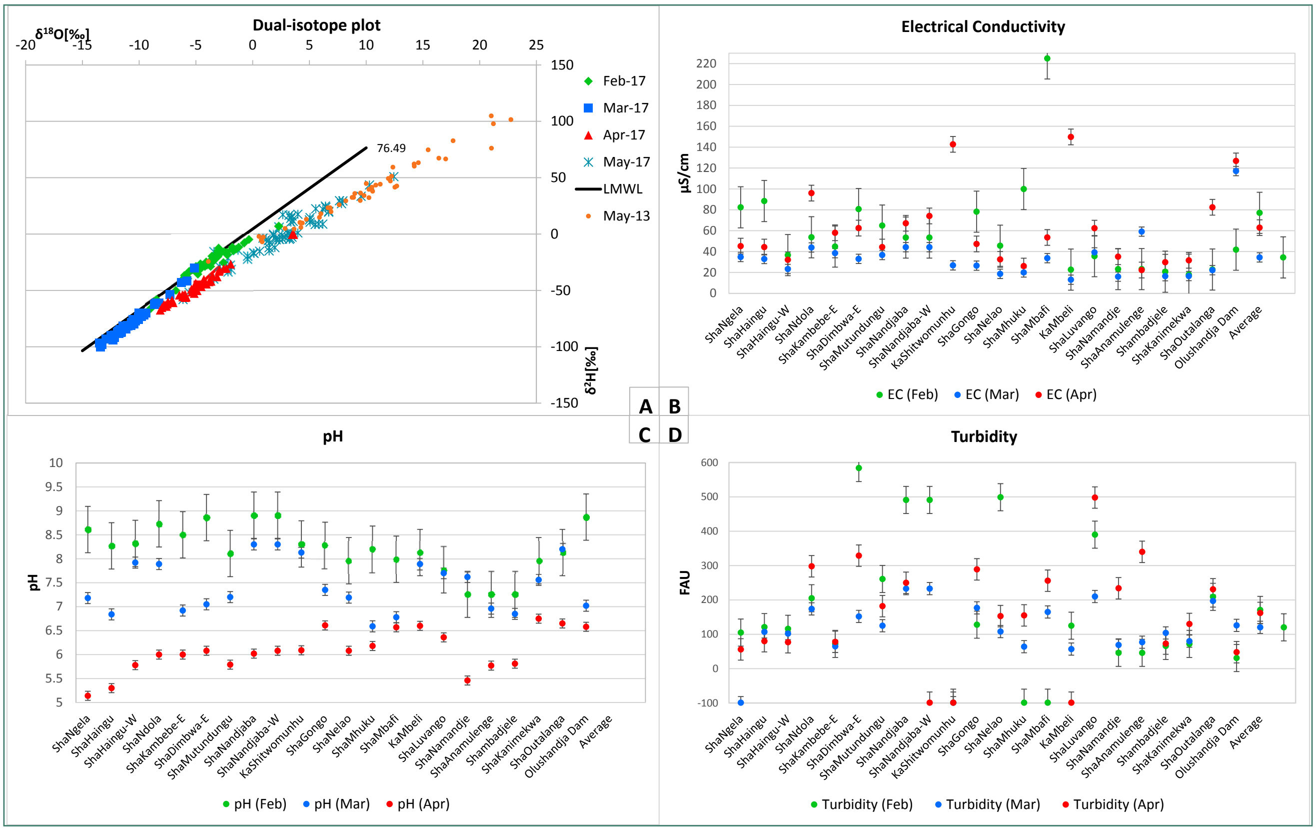


Figure 4: Stable water isotopes (A), EC (B), pH (C), and turbidity (D) following the first major rainfall (February 2017), around the flood peak (March 2017), and post-flood (April 2017) from 22 water bodies (ordered from east to west), which were consistently measured during each field visit. FAU values below 0 (-99) denote that turbidity exceeded the level of the probe. EC values of 481 µS/cm at KaShitwomunhu are not shown due to scale.

was relatively uniform from December onwards, February and March were the wettest months, accounting for more than 50% of the rainfall amount.

Subsequent discharge in iishana varied significantly in space and time. In February, just under 10 of iishana sampled were running at an average of 2.5 m^3/s (maximum recorded 3.6 m^3/s). In mid-March, more than 20 iishana were running and the average discharge increased to 7 m^3/s (maximum recorded, 13 m^3/s). There were more (26) running iishana at the beginning of April, but the average discharge of 2 m^3/s (maximum 5 m^3/s) was the lowest amongst the three field visits. Considering that there are at least 34 major iishana along the traversing 140 km road between the Olushandja Dam, Outapi, Omafo, and Odibo (an average of one oshana for every 4 km in the alluvial plains), a discharge in excess of 200 m^3/s during the flood peak was generated; the nearby Kunene River had a discharge of around 500 m^3/s at Ruacana during the same period (Namibia Hydrological Services, 2017). The dual isotope plot (Fig. 4a) documents well

Table 2: Summary of recharge rates obtained with different methods and for characteristic sites for each landform. Whenever ranges are given, multiple sites for the particular landform (e.g., with different rainfall amounts) were examined and the ranges represent the variation within these.

Landform	Investigated site	Recharge pathway	Recharge rate [mm y^{-1}]
Deep sheet sands, vegetated	Elundu Forest	direct	[*1]Mean: 9–20 mm y^{-1} [*2]Mean: 11 mm y^{-1} [*3]Mean: 5 mm y^{-1} [*2]2013/14: 29 mm y^{-1} [*2]2014/15: 0 mm y^{-1} [*2]2015/16: 4 mm y^{-1}
Deep sheet sands, bare soil	Elundu Forest	direct	[*1]Mean: 9–14 mm y^{-1}
Deep sheet sands, vegetated	Omhito School		[*1]Mean: 17–25 mm y^{-1}
Deep dune sand, vegetated	Omboloka1	direct	[4]2016/17 min: 12.5 mm [4]2016/17 max: 67 mm
Depressions underlain by calcrete	Oshanashiwa	direct/indirect	[*1]2013/14: 31 mm y^{-1} [*4]2016/17 min: 13.5 mm [*4]2016/17 max: 55.8 mm
	Okamanya		[*4]2016/17 mean: 15 mm
	Omboloka2		[*4]2016/17 min: 17 mm [*4]2016/17 max: 91.8 mm
Iishana	Oshakati	indirect	[*1]Mean: 0 mm y^{-1} [*2]2013/14: 0 mm y^{-1} [*2]2014/15: 0 mm y^{-1}
Deflation pans	Elundu Pan	indirect	[*1]Mean: 3–4 mm y^{-1}
Ephemeral riverbeds	Niipele Drainage	direct/indirect	[*1]Mean: 20–56 mm y^{-1}
	Epumbaondjaba		[*4]2016/17 mean: 39.3 mm
Basin mean decadal water storage changes	CEB	direct/indirect	[*5]Mean: 11 mm y^{-1}

[*]Methods of estimation (refer to methods section): [1]chloride mass balance; [2]peak-shift method; [3]isotope depth profiles; [4]groundwater level fluctuation, [5]large-scale approximation based on remote sensing

the continual loss of water by evaporation with the shift toward more enriched isotopic ratios as times passes and evaporation proceeds.

Water quality: surface water

Results from 22 water bodies on the Namibian side of the basin that were sampled on all three occasions are summarised in Fig. 4. Surface water from local rainfall and devoid of upstream input has significantly higher pH values compared to the later sampling of water with additional precipitation and inflow from the upper catchment, when pH lowered to neutral values. Post-flood pH values are consistently below 7. Overall, the highest pH (9.09 at Epako; not shown in the figure) was recorded before the flood, while the lowest (5.14 at Engela) was recorded after the flood.

EC and turbidity values for all sites are lowest in flooding conditions (largely below 100 [average 33] µS/cm and 200 [average 120] FAU, respectively). With few exceptions, no significant difference was recorded before and after the floods for both EC and turbidity. Nevertheless, average EC and turbidity values were relatively higher before the flood than in post-flooding conditions (i.e., 88 vs. 68 µS/cm and 264 vs. 194 FAU for all sites). No distinct spatial pattern emerged from any of the measured parameters.

Water quality: groundwater

For the Ohangwena region, the physico-chemical parameters of the shallow groundwater are in general within the WHO drinking water guidelines. The average temperature was 25°C, and the lowest temperatures were recorded during mornings in winter whereas the highest temperatures were recorded on summer afternoons. EC ranges from 50 to 1,200 µS/cm, and deeper wells are generally more mineralised than shallow wells. Temporal variations in EC are minor. pH is in the neutral range of 7.1 to 7.6. However, turbidity is often problematic, especially for the shallow wells, which showed values up to 255 NTU, whereas for the deeper wells turbidity is always less than 20 NTU.

Hydrochemically, most of the samples from the deeper wells are dominated by Ca^{2+}. Fewer are Na^{+} dominated or have no dominant cations. For the shallow wells, Na^{+} is the most prominent cation. The general order of abundance is $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$ for the deep wells and $Na^{+} > Ca^{2+} > K^{+} > Mg^{2+}$ for the shallow wells. The dominant anion in all deep wells is HCO_3^-. The same largely holds for the shallow wells; only about a third of the samples are dominated by Cl^- and SO_4^{2-}. The abundance of major anions is $HCO_3^- > NO_3^- > Cl^- > SO_4^{2-} > F$ for the deep wells and $HCO_3^- > NO_3^- > SO_4^{2-} > Cl^- > F^-$ for the shallow wells. Ca^{2+}, Mg^{2+}, Na^{+}, Cl^-, and SO_4^{2-} concentrations meet drinking water quality, but some samples have concentrations of K^{+}, NO_3^-, and F^- above permissible limits as recommended by WHO (2011). For shallow wells all cations and anions concentrations meet drinking water quality, with the exception of K^{+}, which is above the limit in 50% of the samples.

The physico-chemical parameters of the shallow groundwater in the Omusati region often make the water unfit for human consumption. EC ranges from 140 to 11,450 µS/cm, and seasonal variations are observed, with increasing salt content during the dry season. pH is in the range of 6.6 to 9.1 and shows larger spatial and temporal variations than for the sampling sites in the Ohangwena region. Turbidity is also often problematic here and reaches values up to 297 NTU.

Hydrochemically, most of the samples from Omusati are of a Ca^{2+}-SO_4^{2-} type; a Na^{+}-HCO_3^- type is seldom encountered. Ca^{2+}, Mg^{2+}, Na^{+}, $Fe^{2+/3+}$, K^{+}, and NO_3^- concentrations are within the limits of drinking water quality, but in 70% of the sampled hand-dug wells the water is unfit for human consumption because of high SO_4^{2-} concentrations. A few samples also exceed the permissible limits for Cl^- (12%), F^- (19%), and Mn^{2+} (13%) as recommended by WHO (2011).

Groundwater recharge

The estimated recharge rates for the investigated sites are summarized in Tab. 2. We refer to Beyer et al. (2015, 2016, 2017), Gaj et al. (2016, 2017), Hamutoko et al. (2017), Koeniger et al. (2016), and Shehu (2015) for detailed information on the studied sites (e.g., soil hydraulic properties, grain sizes, hydraulic conductivity, etc.), methodologies, and descriptions of results.

Discussion

The findings of the presented study are highly relevant for developing a strategy for sustainable management of water resources in the CEB. Three key points are to be pointed out explicitly:

- Surface water from iishana can potentially contribute to the supply of water for various local needs.
- The water quality of both shallow groundwater and surface water in the CEB often is not meeting drinking water quality. Hence, the water requires proper treatment before use, and awareness raising is urgently required.
- The amount of groundwater recharge is limited and its occurrence highly localized. This affects the availability of water.

Water quantity

As the current water supply situation in the basin is already constrained and the imported surface water also needs treatment, the water resources covered in this study can be considered important locally. Rainfall data for the 2016/17 rainy season revealed that an amount around or just above the average rainfall can generate runoff sufficient for triggering floods. Although runoff and subsequent floods lasted for less than three months, iishana generated at its peak flooding approximately half the discharge of the Kunene River at Ruacana (regulated for hydropower generation) during the same period (Namibia Hydrological Services, 2017) – and all this water is available in the iishana system. Existing long-term records (collected since 1941, for a total of 55 years; missing 23 years) reveal that, in addition to a third of drought or lean years, minor floods accounted for just over a third during that period, while medium (20%) and major floods (13%) made up the remaining third (Mendelsohn et al., 2013). On that basis, flood occurrence is relatively common in the basin. If the flooded water were stored in covered systems and not left unattended or in earth dams, the increase in overall salt content because of evaporation, as observed in our study, could be avoided. Practical applications of iishana water harvesting were tested in the CuveWaters project (http://www.cuvewaters.net/). Such water can be used untreated for gardening purposes and livestock watering or, after appropriate treatment, also as drinking water. In times of drought, when precipitation, surface water, and flooding are lacking, the shallow aquifers in the Ohangwena region provide a buffer because they contain groundwater recharged over many years. However, the very low level of groundwater recharge makes it a limited resource, and reliable balancing of abstraction rates against the recharge rates is of utmost importance.

Water quality

Overall, the *surface water* quality during the observation period is acceptable with regard to pH and EC but not with regard to turbidity, which in a few instances had also exceeded the 1,110 FAU limit of the probe. The parameters that make the *groundwater* unfit for human consumption are turbidity, K^+, NO_3^-, and F^- in the Ohangwena region and SO_4^{2-}, Cl^-, F^- and Mn^{2+} in Omusati. Increased SO_4^{2-} and Cl^- are to be attributed to evaporation (evaporation from the unsaturated zone during infiltration, from the very shallow aquifers, directly from the well) and/or the inwash/dissolution of accumulated salts. F^- is usually considered to be a geogenic contaminant. Wanke et al. (2013, 2015) carried out a detailed study on fluoride contamination and its implications. K^+ and NO_3^- are contaminants typically associated with agricultural activities and faecal contamination by animals. Their presence is consistent with observations during fieldwork that livestock watering happens either from a trough close to the well or by allowing livestock to walk into the broad, shallow wells. None of the wells in the study area showed a protection zone, and contaminants can enter the shallow aquifer with the infiltrating precipitation or surface runoff. Microbiological contaminants are beyond the scope of this study, and we refer to Chisenga et al. (2015) for a thorough discussion. Disinfection of the water with chlorination tablets (the most common method in the studied areas) is rather difficult, as turbidity in excess of 1 NTU (WHO, 2011) might prevent effective disinfection by shielding certain microorganisms. In addition, only 50% of the households treat water from hand-dug wells and shallow pits in the Ohangwena region (Italtrend, 2009), and awareness creation needs to be integrated into any strategy for sustainable management of water resources in the CEB.

Groundwater recharge

With the investigations on groundwater recharge to KOH-0 being just one example, valuable insights on recharge processes and recharge amounts in the CEB that can be transferred to other areas were gained. In addition to the site-specific field approaches described herein, we calculated large-scale fluctuations of total water storage changes (i.e., integrated over all aquifers) using well-documented GRACE gravity field satellite data (Rodell et al., 2009; Swenson & Wahr, 2006; Wahr et al., 2004, 2006). The approach followed herein (we refer to Shehu, 2015, for a detailed description of methods) is that total water storage changes from the driest point of one particular year to the subsequent one provide an integrated measure of water changes across all aquifers. Mean water storage changes integrated over the complete basin and all landforms for the years 2002–2016 were estimated to be as high as 11 mm y^{-1} (or ~2% of mean annual precipitation). This – though not equal to groundwater recharge rates per se – can be seen as an indicator that the basin is receiving sufficient water, through either groundwater inflow or direct/indirect groundwater recharge. These figures are also consistent with other work conducted in the CEB (e.g., Wanke et al., 2015) or in Namibia with comparable climatic and geological conditions (e.g., Brunner et al., 2004; Gieske, 1992; Wanke et al., 2008). The site-specific investigations, however, allow a more precise characterization: Generally, the deep sheet sands of the Eastern Sand Zone provide favourable conditions for direct groundwater recharge because of their high porosity and conductivity for water. In regions where trees are abundant, however, the estimated recharge rates obtained might be significantly reduced locally as trees can take up the water from the unsaturated zone and from the groundwater itself. The reason for this is that many of the species present (e.g., *A. erioloba, C. collinum, B. albitrunca*), are capable of developing deep and potentially groundwater-tapping roots (Beyer et al., 2016). For the ephemeral riverbeds and bare soil sites, however, these factors do not apply. Based on the chloride mass balance method, net local recharge rates are the highest here (Tab. 2). The two landforms – namely, iishana and pans – where mainly indirect recharge could occur are not potential recharge areas. No significant groundwater recharge was observed with any of the applied methods. Nevertheless, these landforms are of great importance for livestock water supply after the rainy season and for fishing purposes. The landform where proper recharge estimations remain challenging is the areas underlain by thick calcrete. The numbers estimated using the peak-displacement method (see Tab. 2) can be seen as potential recharge only because the water was accumulating on top of the calcrete layer located around 1.4 m below the surface at the study site. There is potential that this water could infiltrate through preferential flow paths in the calcrete, but it might also be that all the water is lost via transpiration and evaporation. Applying the chloride mass balance method at this site is not appropriate because dissolution effects in the infiltrating and groundwater can change the estimated recharge by magnitudes. For these sites, the estimations obtained via the water-level fluctuation method are more reliable. Nevertheless, these rates are a summation of groundwater inflow (to the depressions) and direct recharge. The main implications for recharge processes and groundwater recharge can be summarized as follows:

- The areas with the highest potential for direct groundwater recharge are non-vegetated areas underlain by deep sheet sands. Recharge in vegetated areas is sporadic and highly dependent on the character of the rainy season (Bahlmann, 2016).
- Indirect groundwater recharge in the CEB is very limited and occurs only from the ephemeral riverbeds. Unlike in the iishana and pan systems, water stored in them is protected from evaporation by a thick sand layer. If local impermeable layers underneath are present (e.g., the riverbed itself), this constitutes a valuable water source for the rural population that can be accessed easily. Geophysical investigations conducted by the BGR (2006) revealed the presence of large volumes of freshwater underneath several ephemeral rivers throughout Namibia. Studies of similar areas have also confirmed increased recharge potential in the old streams (e.g., Morin et al., 2009). In contrast, both iishana and pans are exfiltration rather than infiltration areas. This is supported by field experiments conducted in this area (infiltrometer tests, isotope labelling tests), the presence of swellable clay minerals and the enhanced salinities encountered in this region. However, the importance of ponding surface water in both iishana and pans for the rural population is enormous.
- Recharge in areas underlain by calcrete, such as the Oshanashiwa site, can occur only when preferential pathways (cracks, fissures, old root channels) are present or the calcrete is discontinuous. The magnitude of recharge is highly variable (see Tab. 2) and requires further scientific attention as well as continued local monitoring efforts.

Conclusion

Water resource management in the CEB is highly complex and remains challenging, especially as no local management bodies (e.g., water point committees) for well fields or for surface water bodies exist. Hand-dug wells are and will continue to be the most important water source in remote areas during the dry season. The use of surface water is limited (dam abstractions, size of the water carrier), but further utilisation of seasonal water stored in the iishana and pans offers great potential (e.g., through innovative techniques such as flood water harvesting or construction of *omatale* [earth dams] covered by shade balls). Both surface and shallow groundwater need to be protected, and simple actions such as not washing clothes in the supply canals, fencing and keeping clean of wells, and installing flood- and rainwater harvesting systems can improve the situation substantially. The rural population has generally endured and learned how to deal with short-lived droughts, but governmental efforts are urgently required for viable interventions (i.e., more boreholes in remote areas) (cf. Luetkemeier & Liehr, 2018). Shallow, highly localized perched aquifers also offer great potential for water supply, and further efforts to detect them would be enormously valuable (e.g., use of geophysics). Deep groundwater resources can provide a strategic reserve during droughts, and future research in SASSCAL can determine their specific locations, appropriate drilling techniques, and by which amounts these aquifers are recharged.

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References

Allison, G.B. (1988) A review of some of the physical, chemical and isotopic techniques available for estimating groundwater recharge. *Estimation of natural groundwater recharge* (ed. by I. Simmers), pp. 49–72. Dordrecht: Springer Netherlands.

Water resources

Allison, G.B., Barnes, C.J., Hughes, M. & Leaney, F.W. (1984) Effect of climate and vegetation on oxygen-18 and deuterium profiles in soils. *International Symposium on Isotope Hydrology in Water Resources Development*, pp. 105–122. IAEA-SM-27020. Vienna: International Atomic Energy Agency.

Bahlmann, L. (2016) *Rainfall characteristics and their implications for groundwater recharge in deep vadose zones. A case study in the Cuvelai-Etosha Basin (CEB), Namibia.* MSc thesis, Leibniz Universität Hannover.

Barnes, C.J. & Allison, G.B. (1988) Tracing of water movement in the unsaturated zone using stable isotopes of hydrogen and oxygen. *Journal of Hydrology*, **100**, 143–176.

Beyer, M., Gaj, M., Hamutoko, J.T., Koeniger, P., Wanke, H. & Himmelsbach, T. (2015) Estimation of groundwater recharge via deuterium labelling in the semi-arid Cuvelai-Etosha Basin, Namibia. *Isotopes in Environmental and Health Studies*, **51**, 533–52.

Beyer, M., Gaj, M., Koeniger, P., Hamutoko, J.T., Wanke, H., Wallner, M. & Himmelsbach, T. (2017) Isotopenhydrologische Methoden (^{2}H, ^{18}O) zur Bestimmung der Grundwasserneubildung in Trockengebieten: Potential und Grenzen. *Grundwasser, Themenheft "Hydrogeologie arider und semiarider Gebiete"*. doi: 10.1007/s00767-017-0381-0.

Beyer, M., Koeniger, P., Gaj, M., Hamutoko, J.T., Wanke, H. & Himmelsbach, T. (2016) A deuterium-based labeling technique for the investigation of rooting depths, water uptake dynamics and unsaturated zone water transport in semiarid environments. *Journal of Hydrology*, **533**, 627–643.

Beyer M., Hipondoka M., Hamutoko, J.T. & Wanke, H. (2018) Water resources in the Cuvelai-Etosha Basin. This volume.

BGR (2006) https://www.bgr.bund.de/EN/Themen/Wasser/Projekte/abgeschlossen/TZ/Namibia/oshivelo_caprivi_omaheke_fb_en.html?nn=1546392

Blume, H.P., Zimmermann, U. & Munnich, K.O. (1967) Tritium tagging of soil moisture: the water balance of forested soils. *Isotope and radiation techniques in soil physics and irrigation studies*, pp. 315–332. Vienna: International Atomic Energy Agency.

Brunner, P., Bauer, P., Eugster, M., Kinzelbach, W. (2004) Using remote sensing to regionalize local precipitation recharge rates obtained from the chloride method. *Journal of Hydrology,* **294**, 241–250.

Chen, J.L., Wilson, C.R., Tapley, B.D., Scanlon, B. & Güntner, A. (2016) Long-term groundwater storage change in Victoria, Australia from satellite gravity and in situ observations. *Global and Planetary Change*, **139**, 56–65.

Chisenga, B., Hamutoko, J.T., Chimwamurombe, P.M. & Wanke, H. (2015) Bacteriological analysis of household water from hand-dug wells in the Cuvelai-Etosha Basin of Namibia. Poster presentation at the 16th WaterNet/WARFSA/GWP-SA Symposium, Mauritius.

Gaj, M., Beyer, M., Koeniger, P., Wanke, H., Hamutoko, J.T. & Himmelsbach, T. (2016) In situ unsaturated zone water stable isotope (2H and 18O) measurements in semi-arid environments: a soil water balance. *Hydrology and Earth System Sciences*, **20**, 715-731.

Gaj, M., Kaufhold, S., Koeniger, P., Beyer, M., Weiler, M. & Himmelsbach, T. (2017) Mineral mediated isotope fractionation of soil water. *Rapid Communications in Mass Spectrometry*, **31**, 269–280.

Gaye, C.B. & Edmunds, W.M. (1996) Groundwater recharge estimation using chloride, stable isotopes and tritium profiles in the sands of northwestern Senegal. *Environmental Geology*, **27**, 246–251.

Gieske, A. (1992) *Dynamics of groundwater recharge – a case study in semi-arid eastern Botswana*. Ph.D. thesis, Vrije Universiteit Amsterdam.

Hamutoko, J.T., Wanke, H., Koeniger, P., Beyer, M. & Gaj, M. (2017) Hydrogeochemical and isotope study of perched aquifers in the Cuvelai-Etosha Basin, Namibia. *Isotopes in Environmental and Health Studies*, **53**, 382-399.

Hamutoko, J.T., Wanke, H., Voigt, H.J. (2016) Estimation of groundwater vulnerability to pollution based on DRASTIC in the Niipele Sub-basin of the Cuvelai Etosha Basin, Namibia. *Physics and Chemistry of the Earth*, **93**, 46–54.

Himmelsbach, T., Beyer, M., Wallner, M., Grünberg, I. & Houben, G. (2018) Deep, semi-fossil aquifers in southern Africa: A synthesis of hydrogeological investigations in northern Namibia. This volume.

Huang, T., Pang, Z., Liu, J., Yin, L. & Edmunds, W.M. (2017) Groundwater recharge in an arid grassland as indicated by soil chloride profile and multiple tracers. *Hydrological Processes,* **31**, 1047-1057.

Italtrend (2009) *Namibia Sanitation Situational Analysis Report*.

Koeniger, P., Gaj, M., Beyer, M. & Himmelsbach, T. (2016) Review on soil water isotope based groundwater recharge estimations. *Hydrological Processes*, **30**, 2817–2834.

Lindenmaier, F., Miller, R., Fenner, J., Christelis, G., Dill, H.G., Himmelsbach, T., Kaufhold, S., Lohe, C., Quinger, M., Schildknecht, F., Symons, G., Walzer, A. & van Wyk, B. (2014) Structure and genesis of the Cubango Megafan in northern Namibia: implications for its hydrogeology. *Hydrogeology Journal*, **22**, 1431–2174.

Longuevergne, L., Wilson, C.R., Scanlon, B.R. & Crétaux, J.F. (2013) GRACE water storage estimates for the Middle East and other regions with significant reservoir and lake storage. *Hydrology and Earth System Sciences*, **17**, 4817–4830.

Luetkemeier, R. & Liehr, S. (2018): Drought sensitivity in the Cuvelai-Basin: Empirical analysis of seasonal water and food consumption patterns. This volume.

Mendelsohn, J.M., Jarvis, A. & Robertson, T. (2013) *A profile and Atlas of the Cuvelai-Etosha basin.* Windhoek, Namibia: RAISON & Gondwana Collection.

Mendelsohn, J.M. & Weber, B. (2011) *The Cuvelai Basin, its water and people in Angola and Namibia.* Windhoek, Namibia: Development Workshop & RAISON.

Morin, E., Grodek, T., Dahan, O., Benito, G., Kulls, C., Jacoby, Y., Van Langenhove, G., Seely, M. & Enzel, Y. (2009) Flood routing and alluvial aquifer recharge along the ephemeral arid Kuiseb River, Namibia. *Journal of Hydrology*, **368**, 262–275.

Miller, R.M., Pickford, M. & Senut, B. (2010) The geology, palaeontology and evolution of the Etosha Pan, Namibia: implications for terminal Kalahari deposition. *South African Journal of Geology*, **113**, 307–334.

Namibia Hydrological Services (2017) Daily Flood/Hydrological Drought Bulletin: 17 March 2017. Windhoek, Namibia: Ministry of Agriculture, Water and Forestry.

Rodell, M., Chen, J.L., Kato, H., Famiglietti, J.S., Nigro, J. & Wilson, C.R. (2007) Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE. *Hydrogeology Journal*, **15**, 159–166.

Rodell, M., Velicogna, I. & Famiglietti, J.S. (2009) Satellite-based estimates of groundwater depletion in India. *Nature*, **460**, 999–1002.

Saxena, R.K. (1984) Estimation of groundwater recharge and moisture movement in sandy formations by tracing natural oxygen-18 and injected tritium profiles in the unsaturated zone. *Nordic Hydrology*, 235–242.

Scanlon, B.R. (1991) Evaluation of moisture flux from chloride data in desert soils. *Journal of Hydrology*, **128**, 137–156.

Shehu, B. (2015) *Correction of GRACE data for the influence of surface water, soil and vegetation moisture. A case study on the quantification of groundwater recharge rates in the Cuvelai-Etosha-Basin (CEB), Namibia*. MSc Thesis, Leibniz Universität Hannover.

Swenson, S.C. & Wahr, J. (2006) Post-processing removal of correlated errors in GRACE data, *Geophysical Research Letters,* **33**, L08402. doi:10.1029/2005GL025285

Wahr, J., Swenson, S. & Velicogna, I. (2006) Accuracy of GRACE mass estimates. *Geophysical Research Letters,* **33**, L06401.

Wahr, J., Swenson, S., Zlotnicki, V. & Velicogna, I. (2004) Time-variable gravity from GRACE: First results. *Geophysical Research Letters,* **31**, L11501.

Wallner, M., Houben, G., Lohe, C., Quinger, M. & Himmelsbach, T. (2017) Inverse modeling and uncertainty analysis of potential groundwater recharge to the confined semi-fossil Ohangwena II Aquifer, Namibia. *Hydrogeology Journal*, **25**, 2303–2321.

Wanke, H., Duenkeloh, A. & Udluft, P. (2008) Groundwater recharge assessment for the Kalahari catchment of north-eastern Namibia and north-western Botswana with a large scale water balance model. *Water Resources Management*, **22**, 1143–1158.

Wanke H., Mulike P., Petrus I., Amutenya, D., van Wyk A., Quinger M. & Lohe C. (2013) Towards a management strategy for fluoride threatened groundwater: A case study from Namibia. GeoGen 2013 Conference, February 2013, Addis Ababa, Ethiopia.

Wanke, H., Nakwafila, A., Hamutoko, J.T., Lohe, C., Neumbo, F., Petrus, I., David, A., Beukes, H., Masule, N. & Quinger, M. (2015) Hand dug wells in Namibia: an underestimated water source or a threat to human health? *Physics and Chemistry of the Earth*, **76–78**, 104–113.

World Health Organization (2011). Guidelines for drinking-water quality. Geneva: World Health Organization.

Yeh, P.J.-F., Swenson, S.C., Famiglietti, J.S. & Rodell, M. (2006) Remote sensing of groundwater storage changes in Illinois using the Gravity Recovery and Climate Experiment (GRACE). *Water Resources Research*, **42**, W12203. doi:10.1029/2006WR005374.

Zimmermann, U., Münnich, K.O., Roether, W., Kreutz, W., Schubach, K. & Siegel, O. (1966) Tracers determine movement of soil moisture and evapotranspiration. *Science*, **152**, 346–347.

References [CrossRef]

Allison, G.B. (1988) A review of some of the physical, chemical and isotopic techniques available for estimating groundwater recharge. *Estimation of natural groundwater recharge* (ed. by I. Simmers), pp. 49–72. Dordrecht: Springer Netherlands.

Allison, G.B., Barnes, C.J., Hughes, M. & Leaney, F.W. (1984) Effect of climate and vegetation on oxygen-18 and deuterium profiles in soils. *International Symposium on Isotope Hydrology in Water Resources Development*, pp. 105–122. IAEA-SM-27020. Vienna: International Atomic Energy Agency.

Bahlmann, L. (2016) *Rainfall characteristics and their implications for groundwater recharge in deep vadose zones. A case study in the Cuvelai-Etosha Basin (CEB), Namibia.* MSc thesis, Leibniz Universität Hannover.

Barnes, C.J. & Allison, G.B. (1988) Tracing of water movement in the unsaturated zone using stable isotopes of hydrogen and oxygen. *Journal of Hydrology*, **100**, 143–176. CrossRef

Beyer, M., Gaj, M., Hamutoko, J.T., Koeniger, P., Wanke, H. & Himmelsbach, T. (2015) Estimation of groundwater recharge via deuterium labelling in the semi-arid Cuvelai-Etosha Basin, Namibia. *Isotopes in Environmental and Health Studies*, **51**, 533–52. CrossRef

Beyer, M., Gaj, M., Koeniger, P., Hamutoko, J.T., Wanke, H., Wallner, M. & Himmelsbach, T. (2017) Isotopenhydrologische Methoden (^{2}H, ^{18}O) zur Bestimmung der Grundwasserneubildung in Trockengebieten: Potential und Grenzen. *Grundwasser, Themenheft "Hydrogeologie arider und semiarider Gebiete"*. CrossRef

Beyer, M., Koeniger, P., Gaj, M., Hamutoko, J.T., Wanke, H. & Himmelsbach, T. (2016) A deuterium-based labeling technique for the investigation of rooting depths, water uptake dynamics and unsaturated zone water transport in semiarid environments. *Journal of Hydrology*, **533**, 627–643. CrossRef

Beyer M., Hipondoka M., Hamutoko, J.T. & Wanke, H. (2018) Water resources in the Cuvelai-Etosha Basin. This volume. CrossRef

BGR (2006) https://www.bgr.bund.de/EN/Themen/Wasser/Projekte/abgeschlossen/TZ/ Namibia/oshivelo_caprivi_omaheke_fb_en.html?nn=1546392

Blume, H.P., Zimmermann, U. & Munnich, K.O. (1967) Tritium tagging of soil moisture: the water balance of forested soils. *Isotope and radiation techniques in soil physics and irrigation studies*, pp. 315–332. Vienna: International Atomic Energy Agency.

Brunner, P., Bauer, P., Eugster, M., Kinzelbach, W. (2004) Using remote sensing to regionalize local precipitation recharge rates obtained from the chloride method. *Journal of Hydrology*, **294**, 241–250. CrossRef

Chen, J.L., Wilson, C.R., Tapley, B.D., Scanlon, B. & Güntner, A. (2016) Long-term groundwater storage change in Victoria, Australia from satellite gravity and in situ observations. *Global and Planetary Change*, **139**, 56–65. CrossRef

Chisenga, B., Hamutoko, J.T., Chimwamurombe, P.M. & Wanke, H. (2015) Bacteriological analysis of household water from hand-dug wells in the Cuvelai-Etosha Basin of Namibia. Poster presentation at the 16th WaterNet/WARFSA/GWP-SA Symposium, Mauritius.

Gaj, M., Beyer, M., Koeniger, P., Wanke, H., Hamutoko, J.T. & Himmelsbach, T. (2016) In situ unsaturated zone water stable isotope (2H and 18O) measurements in semi-arid environments: a soil water balance. *Hydrology and Earth System Sciences*, **20**, 715-731. CrossRef

Gaj, M., Kaufhold, S., Koeniger, P., Beyer, M., Weiler, M. & Himmelsbach, T. (2017) Mineral mediated isotope fractionation of soil water. *Rapid Communications in Mass Spectrometry*, **31**, 269–280. CrossRef

Gaye, C.B. & Edmunds, W.M. (1996) Groundwater recharge estimation using chloride, stable isotopes and tritium profiles in the sands of northwestern Senegal. *Environmental Geology*, **27**, 246–251. CrossRef

Gieske, A. (1992) *Dynamics of groundwater recharge – a case study in semi-arid eastern Botswana*. Ph.D. thesis, Vrije Universiteit Amsterdam.

Hamutoko, J.T., Wanke, H., Koeniger, P., Beyer, M. & Gaj, M. (2017) Hydrogeochemical and isotope study of perched aquifers in the Cuvelai-Etosha Basin, Namibia. *Isotopes in Environmental and Health Studies*, **53**, 382-399. CrossRef

Hamutoko, J.T., Wanke, H., Voigt, H.J. (2016) Estimation of groundwater vulnerability to pollution based on DRASTIC in the Niipele Sub-basin of the Cuvelai Etosha Basin, Namibia. *Physics and Chemistry of the Earth*, **93**, 46–54. CrossRef

Himmelsbach, T., Beyer, M., Wallner, M., Grünberg, I. & Houben, G. (2018) Deep, semi-fossil aquifers in southern Africa: A synthesis of hydrogeological investigations in northern Namibia. This volume. CrossRef

Huang, T., Pang, Z., Liu, J., Yin, L. & Edmunds, W.M. (2017) Groundwater recharge in an arid grassland as indicated by soil chloride profile and multiple tracers. *Hydrological Processes*, **31**, 1047-1057. CrossRef

Italtrend (2009) *Namibia Sanitation Situational Analysis Report*.

Koeniger, P., Gaj, M., Beyer, M. & Himmelsbach, T. (2016) Review on soil water isotope based groundwater recharge estimations. *Hydrological Processes*, **30**, 2817–2834. CrossRef

Lindenmaier, F., Miller, R., Fenner, J., Christelis, G., Dill, H.G., Himmelsbach, T., Kaufhold, S., Lohe, C., Quinger, M., Schildknecht, F., Symons, G., Walzer, A. & van Wyk, B. (2014) Structure and genesis of the Cubango Megafan in northern Namibia: implications for its hydrogeology. *Hydrogeology Journal*, **22**, 1431–2174. CrossRef

Longuevergne, L., Wilson, C.R., Scanlon, B.R. & Crétaux, J.F. (2013) GRACE water storage estimates for the Middle East and other regions with significant reservoir and lake storage. *Hydrology and Earth System Sciences*, **17**, 4817–4830. CrossRef

Luetkemeier, R. & Liehr, S. (2018): Drought sensitivity in the Cuvelai-Basin: Empirical analysis of seasonal water and food consumption patterns. This volume. CrossRef

Mendelsohn, J.M., Jarvis, A. & Robertson, T. (2013) *A profile and Atlas of the Cuvelai-Etosha basin.* Windhoek, Namibia: RAISON & Gondwana Collection.

Mendelsohn, J.M. & Weber, B. (2011) *The Cuvelai Basin, its water and people in Angola and Namibia*. Windhoek, Namibia: Development Workshop & RAISON.

Morin, E., Grodek, T., Dahan, O., Benito, G., Kulls, C., Jacoby, Y., Van Langenhove, G., Seely, M. & Enzel, Y. (2009) Flood routing and alluvial aquifer recharge along the ephemeral arid Kuiseb River, Namibia. *Journal of Hydrology*, **368**, 262–275. CrossRef

Miller, R.M., Pickford, M. & Senut, B. (2010) The geology, palaeontology and evolution of the Etosha Pan, Namibia: implications for terminal Kalahari deposition. *South African Journal of Geology*, **113**, 307–334. CrossRef

Namibia Hydrological Services (2017) Daily Flood/Hydrological Drought Bulletin: 17 March 2017. Windhoek, Namibia: Ministry of Agriculture, Water and Forestry.

Rodell, M., Chen, J.L., Kato, H., Famiglietti, J.S., Nigro, J. & Wilson, C.R. (2007) Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE. *Hydrogeology Journal*, **15**, 159–166. CrossRef

Rodell, M., Velicogna, I. & Famiglietti, J.S. (2009) Satellite-based estimates of groundwater depletion in India. *Nature*, **460**, 999–1002. CrossRef

Saxena, R.K. (1984) Estimation of groundwater recharge and moisture movement in sandy formations by tracing natural oxygen-18 and injected tritium profiles in the unsaturated zone. *Nordic Hydrology*, 235–242. CrossRef

Scanlon, B.R. (1991) Evaluation of moisture flux from chloride data in desert soils. *Journal of Hydrology*, **128**, 137–156.

Shehu, B. (2015) *Correction of GRACE data for the influence of surface water, soil and vegetation moisture. A case study on the quantification of groundwater recharge rates in the Cuvelai-Etosha-Basin (CEB), Namibia*. MSc Thesis, Leibniz Universität Hannover.

Swenson, S.C. & Wahr, J. (2006) Post-processing removal of correlated errors in GRACE data, *Geophysical Research Letters*, **33**, L08402. CrossRef

Wahr, J., Swenson, S. & Velicogna, I. (2006) Accuracy of GRACE mass estimates. *Geophysical Research Letters*, **33**, L06401. CrossRef

Wahr, J., Swenson, S., Zlotnicki, V. & Velicogna, I. (2004) Time-variable gravity from GRACE: First results. *Geophysical Research Letters*, **31**, L11501. CrossRef

Wallner, M., Houben, G., Lohe, C., Quinger, M. & Himmelsbach, T. (2017) Inverse modeling and uncertainty analysis of potential groundwater recharge to the confined semi-fossil Ohangwena II Aquifer, Namibia. *Hydrogeology Journal*, **25**, 2303–2321. CrossRef

Wanke, H., Duenkeloh, A. & Udluft, P. (2008) Groundwater recharge assessment for the Kalahari catchment of north-eastern Namibia and north-western Botswana with a large scale water balance model. *Water Resources Management*, **22**, 1143–1158. CrossRef

Wanke H., Mulike P., Petrus I., Amutenya, D., van Wyk A., Quinger M. & Lohe C. (2013) Towards a management strategy for fluoride threatened groundwater: A case study from Namibia. GeoGen 2013 Conference, February 2013, Addis Ababa, Ethiopia.

Wanke, H., Nakwafila, A., Hamutoko, J.T., Lohe, C., Neumbo, F., Petrus, I., David, A., Beukes, H., Masule, N. & Quinger, M. (2015) Hand dug wells in Namibia: an underestimated water source or a threat to human health? *Physics and Chemistry of the Earth*, **76–78**, 104–113.

World Health Organization (2011). Guidelines for drinking-water quality. Geneva: World Health Organization.

Yeh, P.J.-F., Swenson, S.C., Famiglietti, J.S. & Rodell, M. (2006) Remote sensing of groundwater storage changes in Illinois using the Gravity Recovery and Climate Experiment (GRACE). *Water Resources Research*, **42**, W12203. CrossRef

Zimmermann, U., Münnich, K.O., Roether, W., Kreutz, W., Schubach, K. & Siegel, O. (1966) Tracers determine movement of soil moisture and evapotranspiration. *Science*, **152**, 346–347. CrossRef

Water resources in the Cuvelai-Etosha Basin

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The Cuvelai-Etosha Basin (CEB), a transboundary river basin shared almost equally by Angola in the north and Namibia in the south, is home to approximately 40% of the Namibian population. The CEB is an endorheic catchment—that is, there is no outflow of surface water from the basin. Reliable supply of fresh water is an omnipresent issue as there is only one rainy season (November–April) with limited rainfall and no perennial rivers.

It receives summer rainfall, with an annual average of 300 mm in the southwest and 850 mm in the northeast (Mendelsohn & Weber, 2011). February and March are the wettest months. Because of a highly variable rainfall in space and time, both droughts and floods are frequent in the basin. The last recorded major floods occurred in 2008–2011, with medium floods in 2012 and 2017. Drought or lean years occurred from 2014 to 2016. The temperature is on average above 23 °C, and the evaporation rate is up to six times greater (over 3,000 mm y-1) than the average rainfall (Mendelsohn et al., 2013).

While the central parts of the CEB are supplied with drinking water pumped from the Kunene River (Angola) via a canal system, groundwater is the main source of potable water in remote areas. Shallow, wide, and anastomosing channels, locally known as *iishana* (sing. *oshana*), are filled with floodwater from Angola during the rainy season and are common features in the central alluvial plains. In "good" years (i.e., years with high rainfall), iishana create an interconnected, gently flowing river system with water eventually reaching Etosha Pan. Iishana provide fresh water for the ecosystem, livestock, agricultural activities, and drinking during and shortly after the rainy season (they generally dry out in less than four months on average). In the sandy regions in the east and west, surface runoff is nearly nonexistent. Ponding water can be found only in pans – depressions that are seasonally filled with rainwater.

In rural areas the main water resource is local shallow aquifers (*perched aquifers*) that occur as discontinuous small water bodies trapped by impermeable layers within the unsaturated zone. Hand-dug (Fig. 1) wells are owned and/or shared by families, and often villages have more than ten wells in one well field. Normally these hand-dug wells are not covered, and surface runoff including waste matter (e.g., originating from cows) can be washed or blown into the wells. Consequently, having several open wells not only promotes overexploitation of groundwater resources but also increases the risk of groundwater contamination, especially for the shallow aquifers. Livestock watering and agricultural activities also utilise groundwater abstracted from shallow (hand-dug wells; <30 m) or deep (boreholes; >50 m) aquifers as well as the above-mentioned surface water ponding during and shortly after the rainy season in local depressions. In Figure 1, a summary of the most important water resources for the local population is provided. Further details are given in Calunga et al. (2015).

High population density, rapidly growing population, and demand for development and infrastructure in rural areas all add pressure on the limited water resources in the basin, and thorough estimates of the available quantity and quality of all water resources are rare. For effective planning and sustainable management of water resources, a comprehensive understanding of the water system through integrated hydrological and hydrogeological investigations is required (Wanke et al., 2018). The results for the deeper groundwater in the study area are documented by Himmelsbach et al. (2018), Lindenmaier et al. (2014), and Wallner et al. (2017).

References

Calunga, P., Haludilu, T., Mendelsohn, J., Soares, N. & Weber, B. (2015) *Vulnerabilidade na Bacia do Cuvelai / Vulnerability in the Cuvelai Basin, Angola*. Luanda: Development Workshop.

Himmelsbach, T., Beyer, M., Wallner, M., Grünberg, I. & Houben, G. (2018) Deep, semi-fossil aquifers in southern Africa: A synthesis of hydrogeological investigations in northern Namibia. This volume.

Lindenmaier, F., Miller, R., Fenner, J., Christelis, G., Dill, H.G., Himmelsbach, T., Kaufhold, S., Lohe, C., Quinger, M., Schildknecht, F., Symons, G., Walzer, A. & van Wyk, B. (2014) Structure and genesis of the Cubango Megafan in northern Namibia: implications for its hydrogeology. *Hydrogeology Journal*, **22**, 1431–2174.

Mendelsohn, J. M. & Weber, B. (2011) *The Cuvelai Basin, its water and people in Angola and Namibia*. Windhoek, Namibia: Development Workshop & RAISON.

Mendelsohn, J. M., Jarvis, A. & Robertson, T. (2013) *A profile and Atlas of the Cuvelai-Etosha basin*. Windhoek, Namibia: RAISON & Gondwana Collection.

Wallner, M., Houben, G., Lohe, C., Quinger, M. & Himmelsbach, T. (2017) Potential groundwater recharge to the confined semi-fossil Ohangwena II Aquifer, Namibia – Inverse modeling and uncertainty analysis. *Hydrogeology Journal*, accepted for publication.

Wanke, H., Beyer, M., Hipondoka, M., Hamutoko, J.T., Gaj, M., Koeniger, P. & Himmelsbach, T. (2018), The long road to sustainability: integrated water quality and quantity assessments in the Cuvelai-Etosha Basin, Namibia. This volume.

Hand-dug wells ("eendungu", deep wells, up to 30 m deep)

Very commonly, well fields in depressions with numerous wells dug by the local communities can be polluted by animal excrement.

Hand-dug wells (shallow wells, up to 5 m depth, funnel-shaped)

Common in the Eastern Sand Zone (both Namibia and Angola), water is trapped on old river beds (clayey), usually protected by fences. Photo: Nils Wölki

Hand pumps

Hand-operated pumps are often present in rural areas. Cheaper than borehole water, the installations are provided by the government.

Boreholes (engine-operated)

Boreholes drilled by the government exist in many areas in the CEB. Usually, a big tank is filled and then water tapped from there. Expensive for most people.

Calueque–Oshakati water carrier

Open channel connecting the Calueque dam with the township of Oshakati. Most important water source in the western Cuvelai. Water is diverted from the canal and provides tap water for the less poor population until Eenhana.

Iishana

Seasonally flooded (by waters from Angola) depressions which are remainders of an old river system. Important water source for livestock watering and grazing (grasses growing there).

Pans

Seasonally flooded pans, mainly in the Eastern Sand Zone. Different from iishana because filled only by local rain. Used for livestock watering during and after the rainy season.

Artesian and subartesian wells

Confined aquifers are present throughout the CEB. In some places (e.g., near Etosha Pan) the pressure is high enough to create artesian conditions. No energy is needed for pumping.

Figure 1: Water Resources of the Cuvelai-Etosha Basin, Namibia

Groundwater quality, quantity, and recharge estimation on the West Coast of South Africa

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Abstract: Along the west coast of South Africa, where precipitation rates are often less than 400 mm/year and rivers are mostly ephemeral, access to water is a critical limitation on development. However, west coast groundwater is variably saline in areas, can damage sensitive ecological systems, and is often not suitable for domestic or agricultural use. SASSCAL has installed weather and groundwater monitoring instruments along the west coast, with a focus on the RAMSAR-listed Verlorenvlei estuarine lake, to understand the interdependence of domestic, agricultural, and ecological water requirements. Groundwater modelling in the upper parts of the Verlorenvlei catchment intends to show that baseflow from the Krom Antonies tributary is a critical source of low-saline water that also supports economically important agricultural activities. Early results of the Krom Antonies groundwater model suggest that pumping regimes in the Verlorenvlei catchment are at or near maximum capacity. This would suggest that future changes in pumping regimes, through, for example, changes in land use patterns or precipitation patterns would need to be carefully managed to maintain sufficient baseflow supply to the tributaries feeding into the Verlorenvlei estuarine system. Lessons learned in this catchment will be applied to the data-poor Buffels River catchment further north to improve our understanding of west coast hydrology and how it will be affected by future climate change.

Resumo: Ao longo da costa Oeste da África do Sul, onde as taxas de precipitação são frequentemente menores que 400 mm/ano e os rios são essencialmente temporários, o acesso à água é uma limitação crítica para o desenvolvimento. Porém, a água subterrânea na costa Ocidental é variavelmente salina em determinadas áreas, pode prejudicar sistemas ecológicos sensíveis e muitas vezes não é adequada para uso o doméstico ou agrícola. O SASSCAL instalou instrumentos de monitorização meteorológica e de águas subterrâneas ao longo da costa Ocidental, com um foco no Lago Estuarino de Verlorenvlei (Sítio RAMSAR), de modo a compreender a interdependência das necessidades hídricas domésticas, agrícolas e ecológicas. A modelação de águas subterrâneas nas partes superiores da bacia hidrográfica de Verlorenvlei pretende mostrar que o escoamento base do afluente Krom Antonies é uma fonte crítica de água de baixa salinidade, a qual também apoia actividades agrícolas economicamente importantes. Os resultados iniciais do modelo das águas subterrâneas de Krom Antonies sugerem que os regimes de bombeamento na bacia hidrográfica de Verlorenvlei estão próximos ou já na capacidade máxima. Isto sugere que alterações futuras nos regimes de bombeamento, devido a, por exemplo, mudanças nos padrões de uso das terras ou de precipitação, necessitariam de uma gestão cuidadosa, de modo a manter um fornecimento suficiente de escoamento base dos afluentes que alimentam o sistema estuarino de Verlorenvlei. As lições aprendidas nesta bacia hidrográfica serão aplicadas à bacia do Rio Buffels mais a Norte, a qual é pobre em dados, de modo a melhorar a nossa compreensão sobre a hidrologia da costa Oeste e sobre como será afectada no futuro pelas alterações climáticas.

Introduction

The west coast of South Africa is semi-arid in nature, and therefore has very low yearly rainfall, often significantly less than 400 mm, which severely limits both natural recharge to aquifers and the availability of surface water. As a result, water supply for both agricultural and domestic purposes is largely derived from groundwater. Aquifers in this coastal region tend to be (1) primary alluvial aquifers, comprising coastal sands, gravels, and other unconsolidated material, overlying (2) secondary basement aquifers typically of either granitic material or low primary-porosity sandstones, both with relatively low permeability, where groundwater

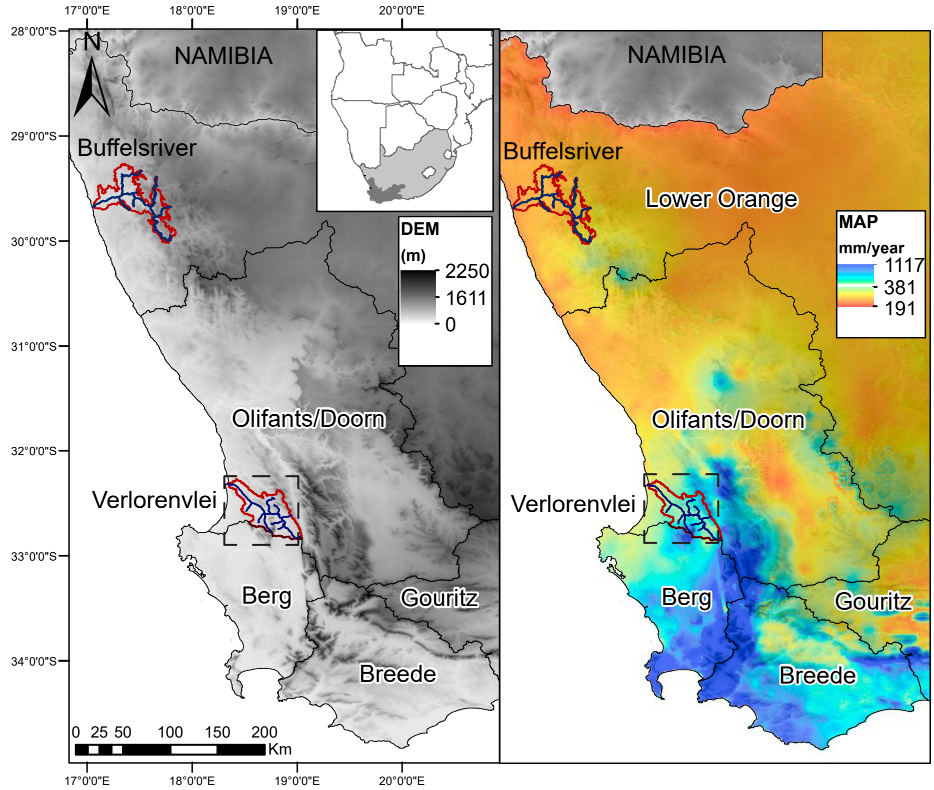

Figure 1: West coast of South Africa, showing catchment management areas for the Buffels, Olifants/Doorn, and Berg rivers as a function of topography (left panel) and mean annual precipitation (MAP) (right panel). Also shown in red are the Verlorenvlei and Buffels river drainage catchments and the location of the Sandveld region (black box) after Lewarne (2009). Inset map showing location of Fig. 1 within South Africa, with the Western Cape of South Africa shown as the darker grey shaded region.

movement is restricted to fractures. Although the unconsolidated, high-porosity nature of the primary aquifers theoretically facilitates rapid recharge, severe evaporative conditions generally result in mean annual recharge of less than 5% of mean annual rainfall (Adams et al., 2004). The net result is the development of moderately to severely saline groundwater associated with the alluvial aquifer systems, with potential contamination to the basement aquifers. The severity of salinization restricts the amount of groundwater that can be used in different

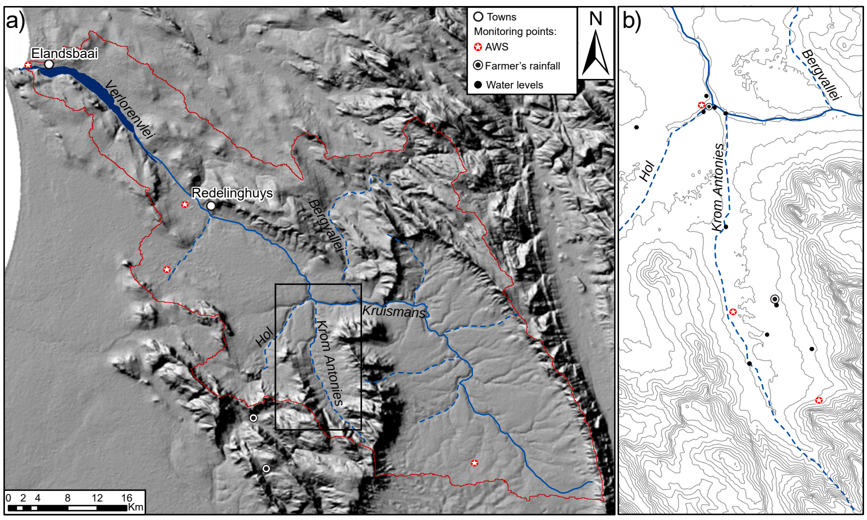

Figure 2: Detailed catchment map for the Verlorenvlei estuarine lake showing the locations of the different feeder tributaries and the regional weather stations. Right panel shows the location of borehole sensors installed as part of this project in the Krom Antonies subcatchment and their position relative to the two AWSs in the Krom Antonies subcatchment (after Watson et al., 2018).

regions. The only other viable sources of water are the three perennial west coast rivers, the Berg, the Oliphants, and the Orange rivers from south to north respectively (Fig. 1).

Despite the limitations in both the quantity and quality of available water resources, the west coast of South Africa is an important agricultural region and is host to a number of biodiversity hotspots. The most significant of these is the Verlorenvlei freshwater estuarine lake system, which lies to the north of the Berg River (Fig. 1). As part of the SASSCAL program, several weather and groundwater monitoring instruments have been installed in the Verlorenvlei catchment (Fig. 2) to better understand the interdependence of rainfall, groundwater recharge, as well as groundwater demand from the various stakeholders. In particular, a key objective is to place constraints on the ecological reserve (Hughes, 2001), the minimum amount of water needed to maintain the ecological health of the Verlorenvlei system. To this end, a detailed groundwater model is being developed. In this contribution, we outline the work that has been done to date in the Verlorenvlei system and discuss how the lessons learned in this catchment might be extrapolated to other west coast catchments with salinity problems, in particular the Buffels River catchment to the west of Springbok (Fig. 1), which is several hundred kilometres north of the Verlorenvlei catchment.

The Verlorenvlei estuarine lake system

The Verlorenvlei estuarine lake system is located in the southern part of the Sandveld, a catchment along the southwestern coast of South Africa (Fig. 1). The area is dominated by sandy soils, and the major vegetation types are Strandveld and coastal Fynbos (Acocks, 1988). The environment has adapted to low rainfall conditions, where coastal rainfall rarely exceeds 400 mm/year, although at higher topographic elevations and further inland, rainfall may reach up to 800 mm/year (Lynch, 2004). The Verlorenvlei estuarine lake is a semi-freshwater lake with


Figure 3: The Verlorenvlei estuarine lake looking west towards the ocean. Photo courtesy of Brian Dyson.

an area of ~15 km^2 (Fig. 2). The lake's unique biodiversity, which is derived from its interaction between fresh and marine water, has resulted in the lake being RAMSAR listed. Rainfall distribution and volumes as well as groundwater abstractions in the catchment are thought to have a critical impact on the water quality and level within the lake (Sidigi et al., 2017; Watson et al., 2018). Decreases in the lake water level result in stagnant and saline conditions, favouring large algal blooms. Water levels have been recorded over the last 17 years, with critically low water levels recorded from 2003 to 2005 and more recently from 2015 to 2016 (Watson et al., 2018).

Hydrology

The estuarine lake is fed by four main rivers or tributaries. These are the Kruismans, Bergvallei, Hol, and Krom Antonies (Fig. 2). Previously, gauging stations existed along the Kruismans and the Hol rivers, but neither of these have been operational since 2009 although there is still active water-level monitoring within the estuarine lake close to Elandsbaai (Fig. 2). Despite no gauging stations currently operating on the Krom Antonies River, it is considered to be the most significant river in terms of both the quality and quantity of flow into the lake. The point on the Kruismans River where these three rivers join is termed the confluence. Below the confluence, the river is variably referred to as the Kruismans River or the Verloren River, but it essentially drains eastwards until the beginning of the actual lake west of Redelinghuis (Fig. 2).

Geology

The catchment geology consists of three major rock units. The oldest rocks in the area are the Neoproterozoic (~750–780 Ma) Malmesbury Group, represented by the Piketberg Formation composed of greywacke, sercitic schist, quartzite, conglomerate, and limestone (Rozendaal & Gresse, 1994). These rocks have been intruded by the Cambrian Cape Granite Suite. The youngest rocks in the catchment are the sedimentary rocks of the Cambrian Table Mountain Group, which overlie both the Malmesbury Group and the Cape Granite Suite. The Table Mountain Group in this area is dominated by three formations. The youngest of these is the Peninsula Formation, which is dominated by sandstones with varying amounts of conglomerate and quartz arenite along with minor shale and has an average thickness of 2000 m (Johnson et al., 2006). The Peninsula Formation is underlain by the Graafwater Formation, which consists of siltstone, shales, and minor sandstone, and has an average thickness of 430 m (Johnson et al., 2006). The Piekenierskloof is the oldest of the Table Mountain Group formations and is made up of coarse-grained sandstone, mudrock, and conglomerates (Johnson et al., 2006).

Hydrogeology

There are three aquifer units within the study area: (1) a primary alluvial aquifer, (2) a secondary aquifer made of shales that have some characteristics of a fractured rock aquifer, and (3) the Table Mountain Group aquifer, which is a fractured rock aquifer. The primary aquifer is made up of quaternary sediments dominated by coarse-grained, clean sand up to 15 m thick, suggesting a high-yielding primary aquifer. Previous recharge estimations for the primary aquifer are between 0.2 and 3.4% of rainfall (Conrad et al., 2004). The secondary aquifer, which underlies the primary aquifer, is made up of Malmesbury Group shales and has a transmissivity of between 0.07 and 7 m^2/day where the aquifer is around 70 m thick (SRK, 2009). The weathering zones, bedding, and fault planes are structural features that control groundwater flow in the secondary aquifer (Conrad et al., 2004). In addition to these two aquifer systems, the Table Mountain Group rocks, which make up the Piketberg Mountains in the hinterland to the Verlorenvlei lake, also constitute a fractured rock aquifer system, where estimates of transmissivity for the Peninsula Formation vary between 15 and 200 m^2/day (Weaver et al., 1999). Groundwater recharge is thought to occur primarily within the high-relief areas dominated by the Table Mountain Group aquifer (Conrad et al., 2004; Eilers, 2018; Watson et al., 2018), similar to other high-lying regions within the Western Cape.

Climate

In the Piketberg Mountains, where the Krom Antonies River originates, the mean annual precipitation (MAP) is around 537 mm/year (Lynch, 2004) (Fig. 3) but can be as high as 800 mm/year. Rainfall declines moving northeast from the Piketberg Mountains, reaching a low of 210 mm/year at the mouth of Verlorenvlei, which is around 50 m above sea level (Lynch, 2004). In summer, daily average air temperatures vary between 17 and 23°C with mean evaporation rates between 5.5 and 7.35 mm/day (Schulze et al., 2007). During winter, daily average air temperatures are between 8 and 13°C, resulting in lower evaporation rates of between 1.5 and 2.3 mm/day (Schulze et al., 2007).

Land use

Agriculture in the Sandveld is the major water user in the area, accounting for 90% of the total water requirements. Potatoes are the main food crop grown in the region, accounting for over 6,600 hectares and using around 20% of total annual recharge (DWAF, 2003). Potatoes in the Sandveld are usually grown in sandy soils, resulting in high yields but requiring high water and fertiliser usage. Tea is the second most grown crop in the catchment, making up around 5,000 hectares (DWAF, 2003), but the majority of the water used is during processing. These crops are also planted in sandy soils and are generally rainfed, and therefore have a limited impact on water resources. Other agricultural activities are citrus and viticulture, which are also high water users. Natural vegetation is also used for livestock grazing.

Data collection

As part of the SASSCAL program, physical infrastructure installed in the catchment was used to capture daily climatic fluctuations as well as groundwater and soil-water responses. Climatic conditions were measured at the confluence of the Krom Antonies, the Hol, and the Kruismans rivers using an Adcon Telemetry automatic weather station (AWS) (Fig. 4a; Muche et al., 2018) and at the foot of the Piketberg Mountains using a Mike Cotton Systems AWS (Fig. 4b). Groundwater was monitored and sampled in the primary and secondary aquifers. In the primary aquifer, 21 piezometers were sampled quarterly, while the water levels and the temperatures in four of these were monitored continuously using pressure transducers (Fig. 4c). In the secondary aquifer, 50 boreholes were sampled quarterly, while the water levels and temperatures in six of these were monitored continuously using pressure transducers. Soil moisture, temperature, and electrical conductivity were monitored at the top (Fig. 4d), middle, and bottom (Fig 4e) of a hillslope near the confluence using Hydraprobes that were installed at different soil textural horizons. Soil textural horizons were matched as best as possible between the three positions (top, middle, and bottom slope) such that different horizons could be traced between the three monitoring locations. Trenches were dug into the soil horizons, the soil moisture probes were installed in groups of three into three different soil horizons on the undisturbed faces of the trenches, and the trenches were subsequently backfilled. Quarterly field trips were undertaken to collect samples, download data, and maintain the instruments.

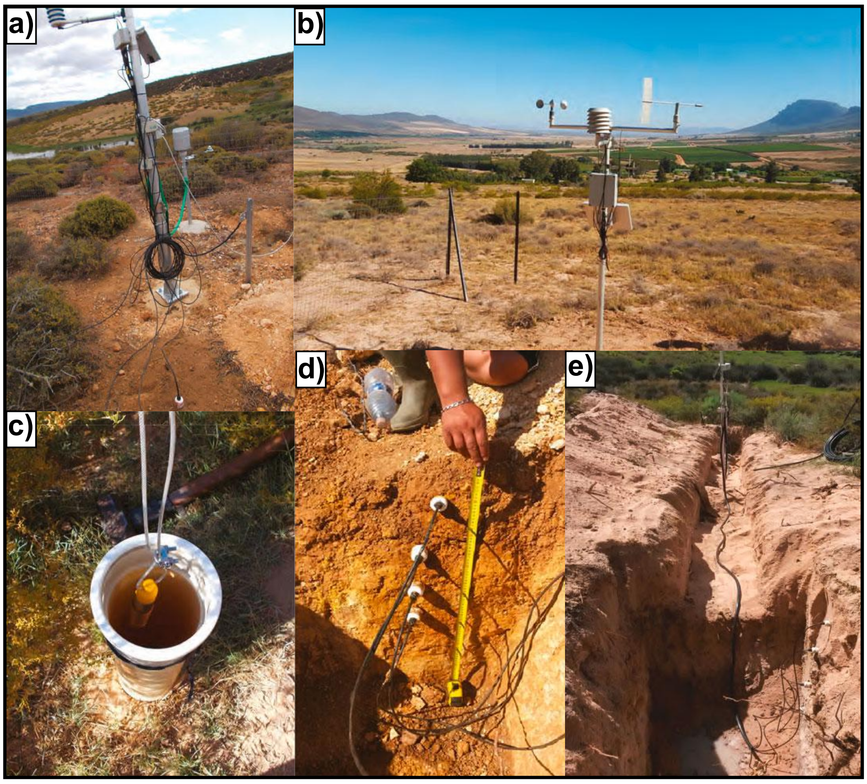

Figure 4: (a) and (b) examples of the AWSs installed in the catchment; (c) type of piezometer with pressure sensor installed in the tributaries to the Verloren River; (d) and (e) installation setup of soil moisture probes. See text for further description of soil moisture probes.

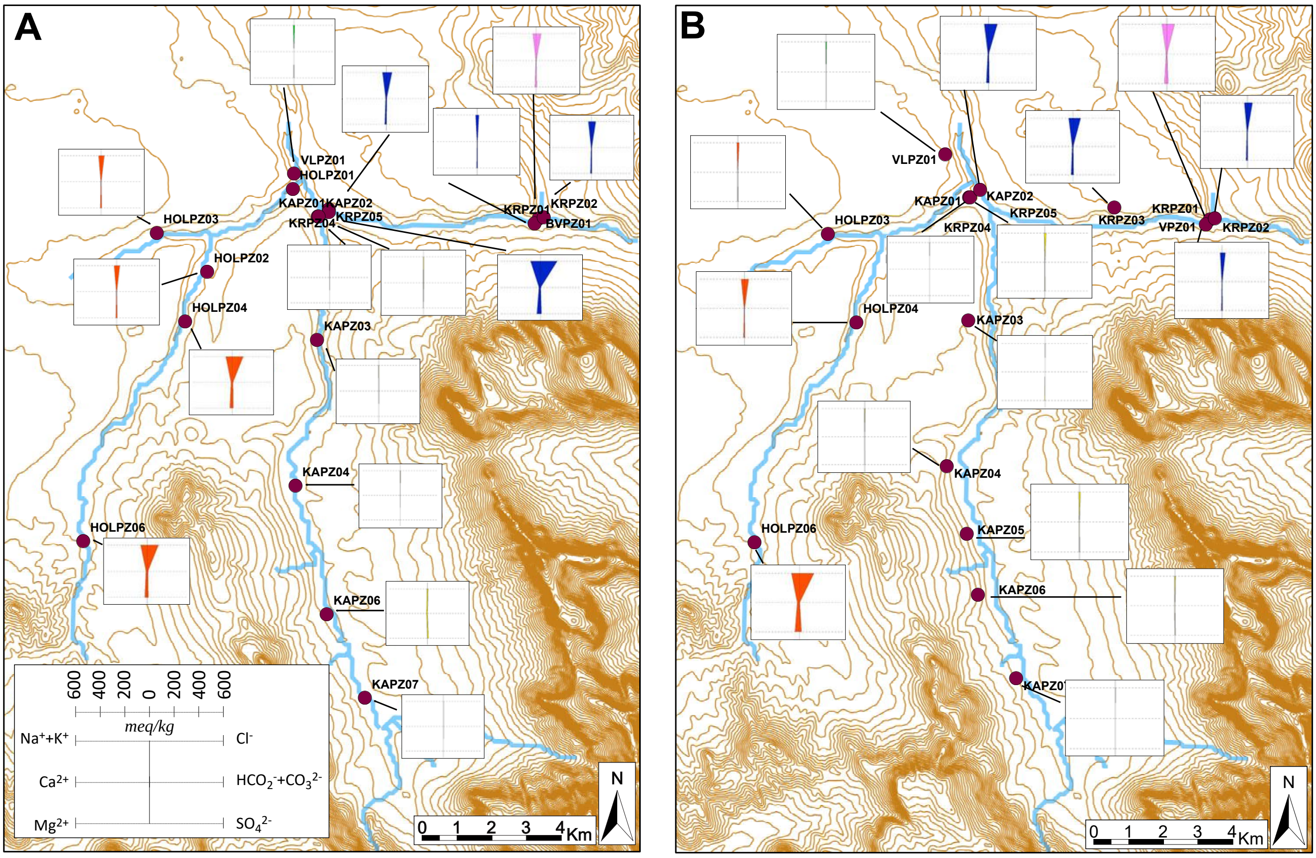

Figure 5: Stiff diagrams showing composition of the shallow groundwater system in the primary aquifer along the four tributaries examined in this study, where panel (a) is for November 2015 (dry season) and panel (b) is for June 2016 (wet season). Note that all stiff diagrams are plotted on the same scale so that relative differences in salt concentrations can be compared. Thus, the stiff diagrams for the Krom Antonies, for example, are very thin because of the low-EC nature of these waters. See lower left box for actual scale on stiff diagrams. HOL = Hol River; KA = Krom Antonies River; KR = Kruismans River; BV = Bergvallei River; VL = Verloren River (Confluence); PZ = Piezometer. Therefore KAPZ04 is piezometer number 4 in the Krom Antonies River. See Fig. 2 for locations.

Results

Surface water and shallow groundwater quality

Surface water and shallow groundwater have similar salinity characteristics in the Verlorenvlei catchment and are generally distinct from the deeper, fresher groundwater system. The Kruismans River has the highest electrical conductivity (EC), ranging from 200 mS/m to 500 mS/m. EC in the Hol River ranges between 400 mS/m and 1,500 mS/m, whilst the EC in the Bergvallei River is between 500 mS/m and 800 mS/m. The Verloren River along with the Krom Antonies River record the lowest salt loads, with EC values between 80 mS/m and 300 mS/m. EC decreases during the rainy season and increases during the dry season for both surface and shallow groundwater, but the surface waters show overall lower concentrations of major cations and anions in comparison to the shallow groundwater. Ions decrease in the order $Na^+ > Cl^- > Mg^{2+} > Ca^{2+} > SO_4^{2-} > HCO_3^- > K^+$ and were used to characterise the geochemical facies of shallow groundwater and surface water for each tributary in the Verlorenvlei catchment. Generally, surface water and shallow groundwater from the Kruismans, Bergvallei, Verlorenvlei, and Hol belong to the same Na-Cl water type. Some samples upstream from the Hol have a Na-Cl-SO_4 water type, while some shallow groundwater samples collected from the same tributary have a Na-Mg-Ca-Cl water type. The Krom Antonies surface water showed a Na-Ca-Mg-Cl water type although some samples had a stronger SO_4^- component and some a stronger HCO_3^- component. Stiff diagrams for all samples though showed a pattern indicative of saline groundwater (Fig. 5). These patterns are similar to the deeper groundwater system in the secondary aquifer underlying the primary aquifer, although the overall ionic strengths are considerably lower than in the shallow primary aquifer (Fig. 6). For the secondary aquifer, average EC values are 74 mS/m for the Kruismans, 123 mS/m for the Krom Antonies, and 147 mS/m for the Hol.

Recharge and groundwater modelling

As part of the goals of this project, a groundwater model will be constructed for the Krom Antonies subcatchment to assess the degree to which the ecological reserve is being met whilst pumping stresses are being applied to the system by the agricultural sector. This groundwater model is being developed based on a detailed analysis of the catchment, taking into account a variety of ranked factors that influence groundwater flow. Spatial and temporal estimations of recharge are essential to the development of this model. In this study, the J2000 rainfall/runoff model was used to estimate daily recharge for the Verlorenvlei catchment (Watson et al., 2018). Based on the results of the recharge modelling, a conceptual model for groundwater flow was developed.

Rainfall/runoff modelling

The J2000 rainfall/runoff model calculates percolation rates by means of simulating processes within the Verlorenvlei catchment. The model includes the following main process steps in calculating recharge: (1) the model subtracts the vegetation interception capacity from rainfall to get net rainfall, (2) runoff water is subtracted from net rainfall based on rainfall intensity and infiltration capacity of the soil, (3) evapotranspiration is supplied by soil moisture and the remaining water is routed further to interflow or recharge, (4) interflow is simulated based on slope factor and the maximum daily soil percolation, and (5) the remainder is allocated to simulated recharge. The J2000 model makes use of hydrological response units (HRUs) for distributed hydrological modelling (Flügel, 1995). The Verlorenvlei catchment was divided into HRUs based on homogenous physiological and topographical features. Soil and climate properties are assigned to each HRU based on available field and literature data. Climate data for the model, including air temperature, relative humidity, wind speed, solar radiation, and rainfall, were obtained from nine weather stations throughout the study catchment. Potential evaporation was calculated using the Penman Monteith evaporation equation, using the above climate data and including a vegetation crop factor. Potential evaporation is assigned to each HRU based on the closest climate monitoring station. To assign rainfall to each HRU, a rainfall correction factor was used, which correlated rainfall with elevation. Farmers' rainfall records were included to improve the rainfall network distribution. The model was calibrated using gauging records from station G3H001 using measured data from 1989 to 2006 (Watson et al., 2018).

Modelled percolation results

The percolation results suggest that simulated potential recharge is higher than that previously estimated (Conrad et al., 2004). Simulated potential recharge values within the catchment varied between

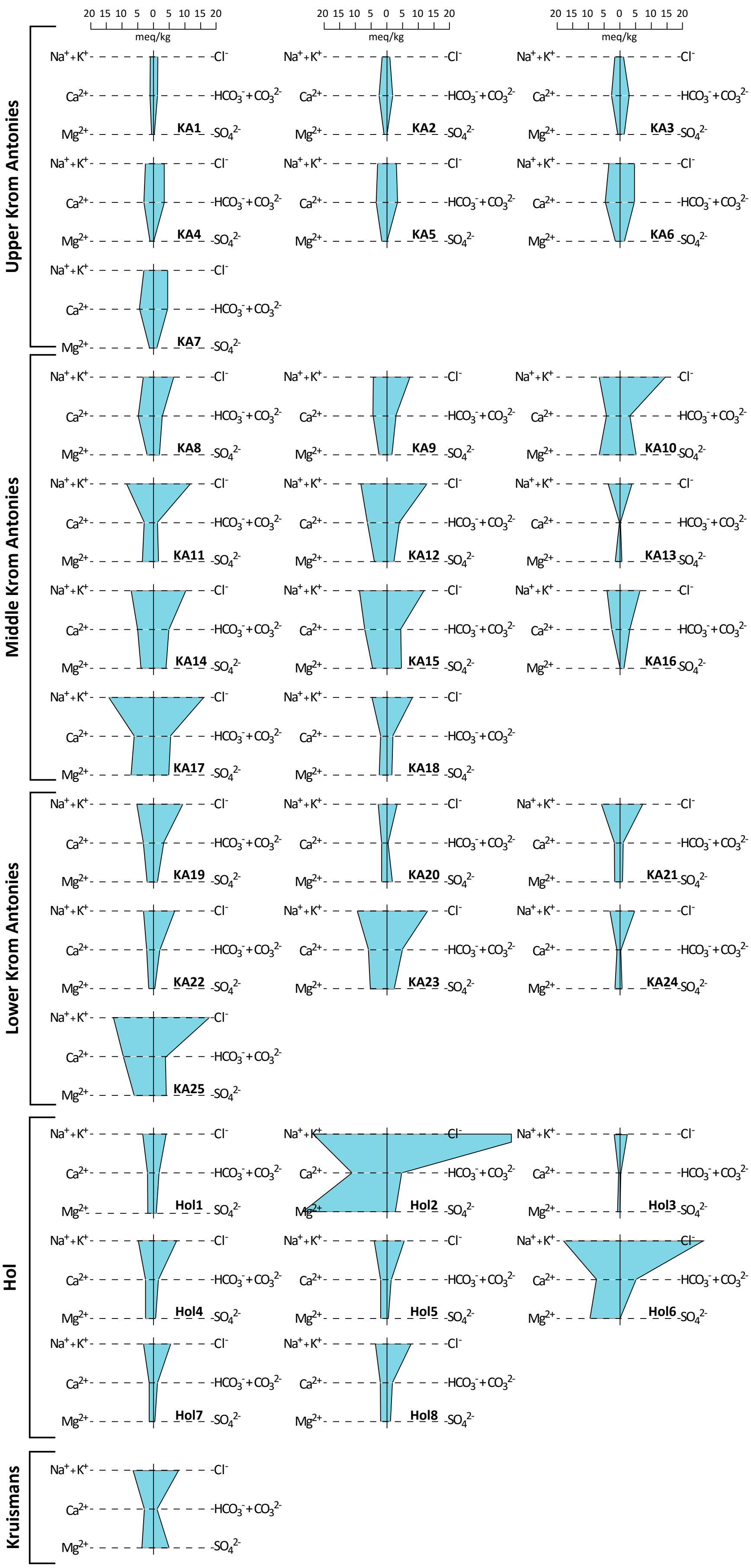

Figure 6: Stiff diagrams showing composition and concentration of cations and anions in the deeper groundwater system within the secondary aquifer. Sample number letters are as per Fig. 5. Low numbers indicate high up in the catchment and higher numbers indicate lower in the catchment towards the confluence.

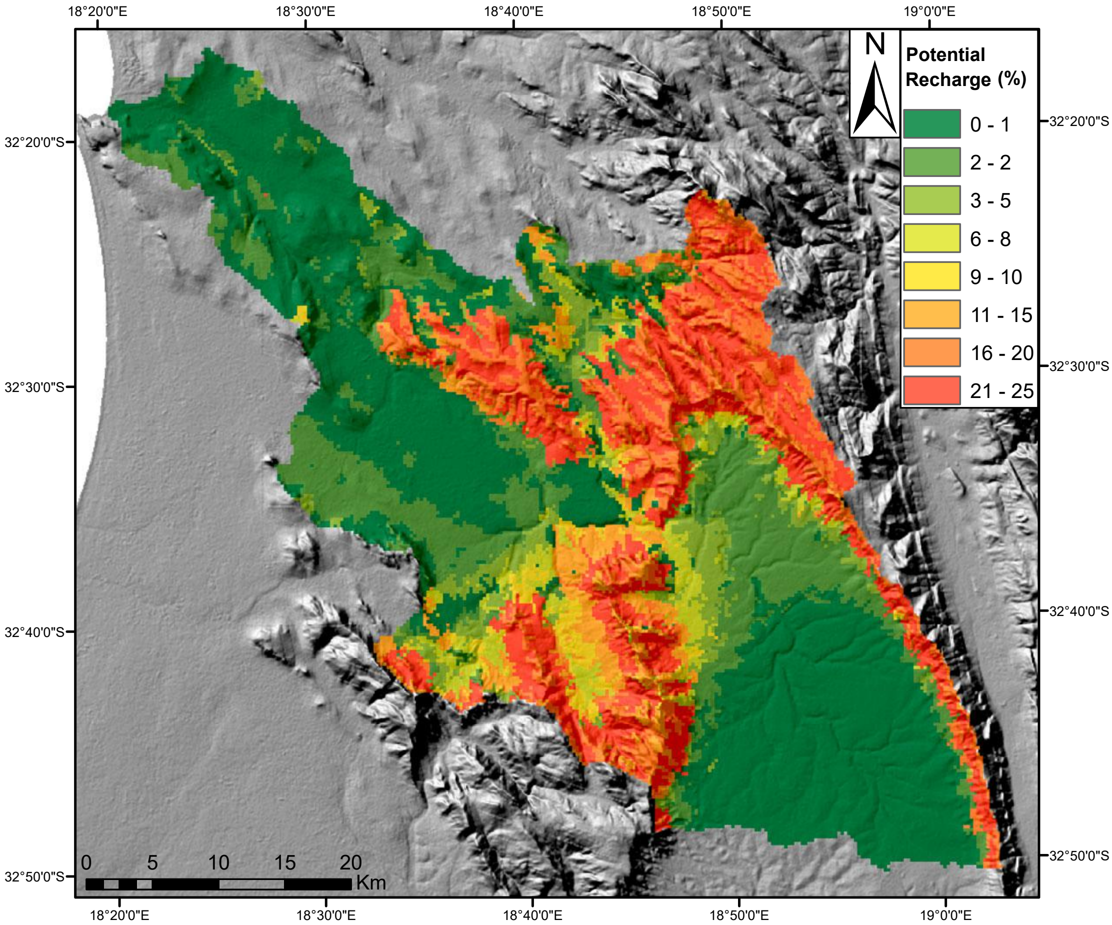

Figure 7: Daily percolation outputs as a function of % median annual rainfall (which equates to potential groundwater recharge rate) for the different hydrological response units (HRUs) defined in the Verlorenvlei catchment.

a median range of 0.7% to 25.12% of rainfall (Fig. 7; Watson et al., 2018). The daily timestep nature of the J2000 model, which incorporates a daily mass balance of evapotranspiration and rainfall, results in higher yearly estimates of potential recharge than from methods such as chloride mass balance or GIS approaches. Daily mass balances allow for higher recharge estimates during winter because of the abundance of rainfall and lower evaporation rates. This result is significant because it explains the apparent discrepancy between the very low calculated recharge rates in semi-arid catchments, through the application of yearly averaging approaches, and the apparent ecological sustainability of most semi-arid catchments.

Although the results above suggest that the system receives more recharge than previously estimated, groundwater abstraction volumes should take into account the needs of the environment. The ecological reserve, which defines the quality and quantity of water needed to sustain the environment, has both peak and low flow requirements. The most critical issue in Verlorenvlei is the impact that groundwater abstractions have on low flows, as these are supplied primarily via groundwater baseflow at times when recharge is low to negligible.

Defining the conceptual groundwater model

The modelled percolation results presented above were used to define a conceptual groundwater model. The main objective of the groundwater model is to understand the maximum pumping volumes possible that will still maintain the ecological reserve during low flow periods. The Krom Antonies catchment is considered to be the main source of groundwater and baseflow to the Verlorenvlei lake system and hence the groundwater model is being developed for this subcatchment of the Verlorenvlei first. The distribution of rainfall across the Krom Antonies catchment is such that the majority of rainfall (450–800 mm/year depending on location within the catchment) is received in the Piketberg Mountains, and the lowest rainfall (210–450 mm/year) is received in the valley of the catchment (Fig. 1b). As a result, the majority of recharge is generated in the Table Mountain Group aquifer in the Piketberg Mountains, where rainfall exceeds evapotranspiration. Very little recharge is received in the primary aquifer located in the valleys, where evapotranspiration exceeds net rainfall. The Table Mountain Group aquifer conveys recharge into the secondary aquifer, which thereafter supplies groundwater flow to the primary aquifer. During the wet season, streamflow is generated primarily from surface runoff in the mountains and valley. Rainwater that is unable to percolate through the Graafwater and Malmesbury shale aquitards also contributes to streamflow. During the dry season, groundwater baseflow is responsible for

Figure 8: The Buffels River catchment looking down from the edge of the escarpment about 50 km west of Springbok.

supplying water to the streams within the catchment. The Krom Antonies subcatchment behaves as though it is a gaining stream, where the groundwater levels in the primary and secondary aquifers allow for baseflow to be generated. When pumping stresses are applied to either the primary or the secondary aquifer, the lowering of the groundwater levels is likely to reduce groundwater baseflow.

Summary and future work

The installation of weather and borehole sensors to model potential recharge and baseflow from the Krom Antonies has facilitated an understanding of the maximum possible recharge volumes that this subcatchment can receive. The use of a daily timestep function in the recharge estimations from the J2000 model produces annual potential recharge estimates that are higher than previous estimates (by up to a factor of 3), with net recharge being less than previous estimates (by a factor of 2 in mountainous regions). Future groundwater modelling using these data, along with delineated aquifer hydraulic conductivities, aquifer storage properties, and localised and regional baseflow, will aim to provide quantitative estimates of the sustainable pumping regimes for the agricultural sector in this region. Because the Krom Antonies has been considered the primary recharge area for the Verlorenvlei catchment as a whole, groundwater modelling in this part of the catchment will also be used to determine the minimum water flow (based on lake water level) and quality thresholds (based on WHO water quality guidelines) for the Verlorenvlei estuarine lake. One important constraint is the contribution that baseflow from the Bergvallei River has to the total flows into the estuarine lake. Although this river was initially thought to be a minor contributor, daily flow rates from the J2000 model suggest that the Bergvallei might contribute up to 20% of freshwater inflows to the estuarine lake, although it is not clear whether these inflows are coming from the shallow (moderately saline) or deep (less saline) groundwater systems. Ongoing work focusing on O, H, and Sr isotopes indicates that there may be a contribution from a Table Mountain Group aquifer system within the Bergvallei subcatchment and that this system is also critical in balancing saline inflows into the lake. Future work will evaluate the relative contributions of all the tributaries into the Verlorenvlei system through the ongoing development of a comprehensive numerical finite-difference (MODFLOW) groundwater flow model coupled to the J2000 outputs and using stream discharge rates and isotopic tracers to evaluate the model results. By coupling these two models together, the fully integrated results generated will provide a comprehensive assessment of the groundwater surface water interactions and flow volumes in the upper parts of the Verlorenvlei catchment. The J2000 model will be used to translate potential recharge received from rainfall into the primary and Table Mountain Group aquifers, while the MODFLOW model will translate potential recharge into a yearly net recharge value based on geological hydraulic conductivities and aquifer drawdown.

The Buffels River catchment

As can be seen from the Verlorenvlei case study, the construction of a groundwater model to determine the sustainability of groundwater abstraction generally requires a network of monitoring boreholes and detailed weather data. Due to the associated costs, many catchments, particularly in Africa, are data poor, and consequently groundwater models are not constructed or are poorly calibrated. Whilst a primary objective of this work is to develop a groundwater model for the Verlorenvlei catchment, the secondary objective is to test how transferable the model results will be to catchments where there are fewer monitoring data available. The Buffels River catchment (Fig. 8) in the Northern Cape of South Africa (Fig. 1) shares many similarities with the Verlorenvlei catchment. Both are semi-arid to arid coastal catchments where the dominant land use is agriculture and where groundwater is variably saline. Each consists of a primary aquifer overlying a secondary aquifer system consisting of fractured or crystalline rock. However, whereas the Verlorenvlei catchment is relatively well monitored, the Buffels River catchment is data poor, with limited weather-monitoring data and rainfall records, no long-term monitoring of water levels within the aquifer system, and no discharge data (actual or modelled) for the river and tributary networks. In spite of these limitations, ongoing groundwater sampling in the catchment has established the hydrochemical and isotopic character of the groundwater. EC levels in the Buffels River are moderately to extremely high, with maximum EC levels of ~1,900 mS/cm. High EC levels are recorded mostly in the alluvial aquifer, and groundwater from the secondary aquifer tends to be fresher, whilst isolated springs present in the region have the lowest EC levels. Sr, O, and H isotope data from both the primary aquifer and the secondary aquifer allow some constraints to be placed on relative flow paths and the role of fluid rock interaction, particularly with the granitic basement gneisses. Once the groundwater model for the Krom Antonies subcatchment described above has been developed and calibrated, it is intended to apply this model to the Buffels River catchment to establish the boundary conditions of the ecological reserve and to better understand the origin and spatial distribution of the saline groundwaters.

Conclusions

Establishing the boundary conditions of groundwater flow and understanding the distribution and transportation of groundwater salts are critical to enable the construction of accurate groundwater models for the west coast of South Africa. The installation of weather and groundwater monitoring equipment in the Verlorenvlei catchment has been essential in the development of a comprehensive conceptual model that forms the foundation for development of a groundwater model for the Krom Antonies subcatchment. The most critical step in this process was the detailed characterisation of recharge through the calculation of daily percolation rates using the J2000 model. The paradox of low recharge rates but apparent sustainability of semi-arid and arid catchments can potentially be resolved by this daily timestep approach. However, groundwater models need proper geochemical and physical characterisation of the groundwater system in order to be accurately constructed and calibrated. In the Verlorenvlei catchment, modelled discharge rates for the different tributaries were combined with isotope characterisation of the primary and secondary aquifers to understand the role of each tributary. Preliminary results have indicated that although the Krom Antonies has historically been considered the primary source of freshwater inflows to the Verlorenvlei lake system, additional inflows from the Bergvallei tributary are more important than previously thought. Early results of the Krom Antonies groundwater model suggest that pumping regimes in the Verlorenvlei catchment are at or near maximum capacity. Thus, future changes in pumping regimes through, for example, changes in land use patterns or precipitation patterns would need to be carefully managed to maintain sufficient baseflow supply to the tributaries feeding into the Verlorenvlei estuarine lake system. The groundwater model developed for the Verlorenvlei region will be further evaluated by assessing the transferability of the groundwater model to the Buffels River catchment, where similar boundary conditions exist (mean annual precipitation, evapotranspiration rates, recharge rates, salinity profiles, etc.) and the same suite of isotopic tracers exist (O, H, Sr), but few monitoring data are available. Establishing the transferability of such a groundwater model would be a valuable step in understanding the groundwater dynamics in catchments that have even fewer data available, a situation that is still too common in large parts of Africa.

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References

Acocks, J. (1988) *Veld types of South Africa*, 3rd edition. Memoirs of Botanical Survey of South Africa 57.

Adams, S., Titus, R. & Xu, Y. (2004) *Groundwater recharge assessment of the basement aquifers of central Namaqualand*. Water Research Commission Report 1093/1/04, Pretoria, South Africa.

Conrad, J., Nel, J. & Wentzel, J. (2004) The challenges and implications of assessing groundwater recharge: a case study – northern Sandveld, Western Cape, South Africa. *Water SA*, **30**, 75–81.

DWAF (2003) *Sandveld preliminary (rapid) reserve determinations. Langvlei, Jakkals and Verlorenvlei Rivers. Olifants-Doorn WMA G30.* Surface Volume 1: Final Report Reserve Specifications. DWAF Project Number 2002-227.

Eilers, A. (2018) Deep groundwater characterisation and recharge estimation in the Verlorenvlei catchment. MSc thesis, Stellenbosch University.

Flügel, W. (1995) Delineating hydrological response units by geographical information system analyses for regional hydrological modelling using PRMS/MMS in the drainage basin of the River Bröl, Germany. *Hydrological Processes*, **9**, 423–436.

Hughes, D.A. (2001) Providing hydrological information and data analysis tools for the determination of ecological instream flow requirements for South African rivers. *Journal of Hydrology*, **241**, 140–151.

Johnson, M.R., Anhauesser, C.R. & Thomas, R.J. (2006) *The geology of South Africa*. Geological Society of South Africa, Pretoria, 691

Lewarne, M. (2009) Setting up ARCSWAT hydrological model for the Verlorenvlei catchment. MSc thesis, Stellenbosch University.

Lynch, S. (2004) *Development of a raster database of annula, monthly and daily rainfall for southern Africa*. Water Research Commission Report 1156/1/04, Pretoria, South Africa.

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: history, state of Measuring Network, database and online presentation, challenges & success. This volume.

Rozendaal, A. & Gresse, P.G. (1994) Structural setting of the Riviera W-Mo deposit, Western Cape, South Africa. *South African Journal of Geology*, **97**, 184.

Schulze, R.E., Maharaj, M., Warburton, M.L., Gers, C.J., Horan, M.J.C., Kunz, R.P. & Clark, D.J. (2007) *South African atlas of climatology and agrohydrology*. Water Research Commission Report 1489, Pretoria, South Africa.

Sidigi, N.T., Miller, J.A., Watson, A.P., Clarke, C.E., & Butler, M. (2017) Geochemical and isotopic tracing of salt loads into the RAMSAR listed Verlorenvlei estuarine lake, South Africa. *Procedia Earth and Planetary Science*, **17**, 909–912.

SRK (2009) *Preliminary assessment of impact of the proposed Riviera Tungsten Mine on groundwater resources*. SRK Consulting, Rondebosch, South Africa.

Watson, A., Miller, J., Fleischer, M. & de Clercq, W. (2018) Estimation of groundwater recharge via percolation outputs from a rainfall/runoff model for the Verlorenvlei estuarine system, west coast, South Africa. *Journal of Hydrology*, **558**, 238–254.

Weaver, J., Talma, A. & Cave, L. (1999) *Geochemistry and isotopes for resource evaluation in the fractured rock aquifers of the Table Mountain Group*. Water Research Commission Report 481/1/99, Pretoria, South Africa.

References [CrossRef]

Acocks, J. (1988) *Veld types of South Africa*, 3rd edition. Memoirs of Botanical Survey of South Africa 57.

Adams, S., Titus, R. & Xu, Y. (2004) *Groundwater recharge assessment of the basement aquifers of central Namaqualand*. Water Research Commission Report 1093/1/04, Pretoria, South Africa.

Conrad, J., Nel, J. & Wentzel, J. (2004) The challenges and implications of assessing groundwater recharge: a case study – northern Sandveld, Western Cape, South Africa. *Water SA*, **30**, 75–81.

DWAF (2003) *Sandveld preliminary (rapid) reserve determinations. Langvlei, Jakkals and Verlorenvlei Rivers. Olifants-Doorn WMA G30.* Surface Volume 1: Final Report Reserve Specifications. DWAF Project Number 2002-227.

Eilers, A. (2018) Deep groundwater characterisation and recharge estimation in the Verlorenvlei catchment. MSc thesis, Stellenbosch University.

Flügel, W. (1995) Delineating hydrological response units by geographical information system analyses for regional hydrological modelling using PRMS/MMS in the drainage basin of the River Bröl, Germany. *Hydrological Processes*, **9**, 423–436. CrossRef

Hughes, D.A. (2001) Providing hydrological information and data analysis tools for the determination of ecological instream flow requirements for South African rivers. *Journal of Hydrology*, **241**, 140–151. CrossRef

Johnson, M.R., Anhauesser, C.R. & Thomas, R.J. (2006) *The geology of South Africa*. Geological Society of South Africa, Pretoria, 691

Lewarne, M. (2009) Setting up ARCSWAT hydrological model for the Verlorenvlei catchment. MSc thesis, Stellenbosch University.

Lynch, S. (2004) *Development of a raster database of annula, monthly and daily rainfall for southern Africa*. Water Research Commission Report 1156/1/04, Pretoria, South Africa.

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: history, state of Measuring Network, database and online presentation, challenges & success. This volume. CrossRef

Rozendaal, A. & Gresse, P.G. (1994) Structural setting of the Riviera W-Mo deposit, Western Cape, South Africa. *South African Journal of Geology*, **97**, 184.

Schulze, R.E., Maharaj, M., Warburton, M.L., Gers, C.J., Horan, M.J.C., Kunz, R.P. & Clark, D.J. (2007) *South African atlas of climatology and agrohydrology*. Water Research Commission Report 1489, Pretoria, South Africa.

Sidigi, N.T., Miller, J.A., Watson, A.P., Clarke, C.E., & Butler, M. (2017) Geochemical and isotopic tracing of salt loads into the RAMSAR listed Verlorenvlei estuarine lake, South Africa. *Procedia Earth and Planetary Science*, **17**, 909–912. CrossRef

SRK (2009) *Preliminary assessment of impact of the proposed Riviera Tungsten Mine on groundwater resources*. SRK Consulting, Rondebosch, South Africa.

Watson, A., Miller, J., Fleischer, M. & de Clercq, W. (2018) Estimation of groundwater recharge via percolation outputs from a rainfall/runoff model for the Verlorenvlei estuarine system, west coast, South Africa. *Journal of Hydrology*, **558**, 238–254. CrossRef

Weaver, J., Talma, A. & Cave, L. (1999) *Geochemistry and isotopes for resource evaluation in the fractured rock aquifers of the Table Mountain Group*. Water Research Commission Report 481/1/99, Pretoria, South Africa.

Determinants of spatio-temporal variability of water quality in the Barotse Floodplain, western Zambia

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Abstract: Developing a water quality database for the Upper Zambezi Basin is becoming crucial for ensuring strengthened water resources monitoring and management in the face of potential threats posed by anthropogenically induced effects of land use and climate change. To realise this goal, it is important to establish factors that control the variation of water quality. Thus, in this study, we analysed water quality and stream sediment parameters to infer their spatio-temporal variation between 2014 and 2015 in the Barotse Floodplain, western Zambia. It was found that the concentrations of heavy metals (i.e., copper, lead, cadmium, mercury, arsenic, zinc, and chromium) were mostly below detection limits (< 0.002 mg/l) and fell within the World Health Organization (WHO) and Zambia Bureau of Standards (ZABS) guidelines for drinking water. This suggested that current large-scale mining activities taking place upstream of the Barotse Floodplain have no effect on this important water resource. It was the potentially geogenically derived elements, particularly calcium, that were observed to be predominant and appeared to be influenced by physical parameters, especially pH. Seasonal nutrient recruitment was also noted to be active and attributed to land use change and flood inundation patterns. Nitrates spiked up to > 24 mg/l in the year 2014, which experienced higher floods. This value dropped to < 0.5 mg/l in 2015, possibly as a result of below-normal rainfall that led to lower floods. Analysis of bacteriological results indicated that anthropogenic activities affected water quality. All sampling points close to communities registered a too-numerous-to-count (TNTC) concentration of faecal and total coliforms (> 200 coliforms/100 ml). An assessment of the sediment yields predicted by the Soil and Water Assessment Tool (SWAT) and measured turbidity suggested the likely existence of a stronger relationship in the upstream areas and near the confluence of the Zambezi and the Luanginga Rivers than within and after the main floodplain. Because of the limited sampling period, however, this phenomenon was not conclusively assessed. Nevertheless, the observed lower turbidity levels and element concentrations in the floodplain may be a strong indicator of a critical role that the Barotse Floodplain plays as a natural sink.

Resumo: É cada vez mais crucial o desenvolvimento de uma base de dados sobre a qualidade da água da bacia superior do Zambezi, de modo a garantir a monitorização e gestão reforçada dos recursos hídricos face a potenciais ameaças, causadas pelos efeitos antropogénicos resultantes do uso das terras e das alterações climáticas. De modo a materializar este objectivo, é importante estabelecer factores que controlam a variação da qualidade da água. Assim, neste estudo, analisámos a qualidade da água e os parâmetros dos sedimentos da corrente, de modo a inferir a sua variação espacio-temporal entre 2014 e 2015 na Planície Aluvial de Barotse, na Zâmbia Ocidental. Verificou-se que as concentrações de metais pesados (i.e. cobre, chumbo, cádmio, mercúrio, arsénio, zinco e crómio) encontravam-se essencialmente abaixo dos limites de detecção (< 0.002 mg/l), sendo abrangidas pelas normas da Organização Mundial da Saúde (OMS) e da Zambia Bureau of Standards (ZABS) para a água potável. Isto sugere que as actividades mineiras actuais de grande escala a decorrerem a montante da Planície Aluvial de Barotse não têm nenhum efeito neste importante recurso hídrico. Os elementos potencialmente geogénicos, particularmente o cálcio, foram observados como predominantes, parecendo ser influenciados por parâmetros físicos, em especial o pH. O recrutamento sazonal de nutrientes foi também observado como activo e atribuído às alterações do uso da terra e aos padrões de inundação. Os nitratos aumentaram até > 24 mg/l no ano de 2014, o qual sofreu inundações mais elevadas. Este valor caiu para < 0,5 mg/l em 2015, possivelmente devido à ocorrência de precipitação abaixo do normal, que resultou em inundações menos acentuadas. A análise dos resultados bacteriológicos indicou que as actividades antropogénicas afectaram a qualidade da água. Todos os pontos de amostragem perto de comunidades registaram concentrações de coliformes fecais e totais incontáveis (Too-Numerous-To-Count ou TNTC) (> 200 coliforms/100 ml). Uma avaliação dos rendimentos dos sedimentos previstos pela Ferramenta de Avaliação do Solo e da Água (SWAT) e turbidez medida sugere a provável existência de uma relação mais forte nas áreas a montante e junto à confluência dos rios Zambezi e Luanginga que no interior da e após a principal planície aluvial. No entanto, devido ao período limitado de amostragem, este fenómeno não foi definitivamente avaliado. Não obstante, os baixos níveis de turbidez observados e a concentração de elementos na planície aluvial podem possivelmente ser um forte indicador do papel crítico da Planície Aluvial de Barotse como um sumidoro natural.

Introduction

Floodplains are of great cultural and economic importance, as most early civilisations arose in fertile floodplains (Polunin, 2014). Throughout history, people have exploited the floodplains for their rich resources, particularly the alluvial soils, which support crop production. Consequently, floodplains have served as focal points for urban development (Naiman et al., 2005). Floodplains are described as dynamic systems that are shaped by repeated erosion and deposition of sediments, inundation or prolonged hydroperiods during rising water levels, and complex ground-surface water exchange processes. This dynamic nature makes floodplains among the most biologically productive and diverse ecosystems on Earth (Gregory et al., 1991; Naiman & Décamps, 1997; Tockner & Stanford, 2002; Naiman et al., 2005). A study of the spatial extent of all tropical wetlands reveals that 2.5 to 3.5% of Earth's surface is wetlands, with areas of > 10^6 km^2 in South America and 10^5 km^2 in Africa (Tockner & Stanford, 2002; Zuijdgeest et al., 2015).

Wetlands or floodplains are widely regarded as important locations for the uptake and transformation of nutrients and sediment in fluvial landscapes (Noe & Hupp, 2007). Research by Ahiablame et al. (2010) describes sediments as probably the most influential determinant of the ability of the system to process and sustain nutrient loads. This is because floodplains are frequently thought of as sinks of inorganic nutrients and sources of organic nutrients — in other words, nutrient transformers (Noe & Hupp, 2007). Moreover, many agrochemicals, heavy metals, and nutrients chemically bind to sediments, which provide a transport mechanism for these contaminants as well as substrate where they react (Lovett et al., 2007). Zuijdgeest et al. (2015) also crucially point out that flows are restricted in most lakes and floodplains systems; hence, particles have time to settle.

The agrochemical, heavy metal, and nutrient contaminants may be caused by anthropogenic perturbations, which can lead to alterations of the physical, chemical, and biological properties of the water body (Bilotta & Brazier, 2008). Nutrient contaminants can be categorised with respect to where they are being discharged. Writing on 'modeling the relationship between land use and surface water quality', Tong & Chen (2002) state that runoff from different types of land use may be enriched with different kinds of contaminants, which may come from agricultural lands enriched with nutrients, highly developed urban areas (mines inclusive) enriched with rubber fragments, oil, and heavy metals as well as sodium and sulphates from road de-icers. Only contaminants resulting from agricultural land use and mining activities are relevant in the present study area.

In this study, we assessed spatio-temporal variations in water quality parameters of the Barotse Floodplain in light of increasing anthropogenic activities such as farming around this water resource, and mining activities upstream in the Kabombo River Basin of north-western Zambia.

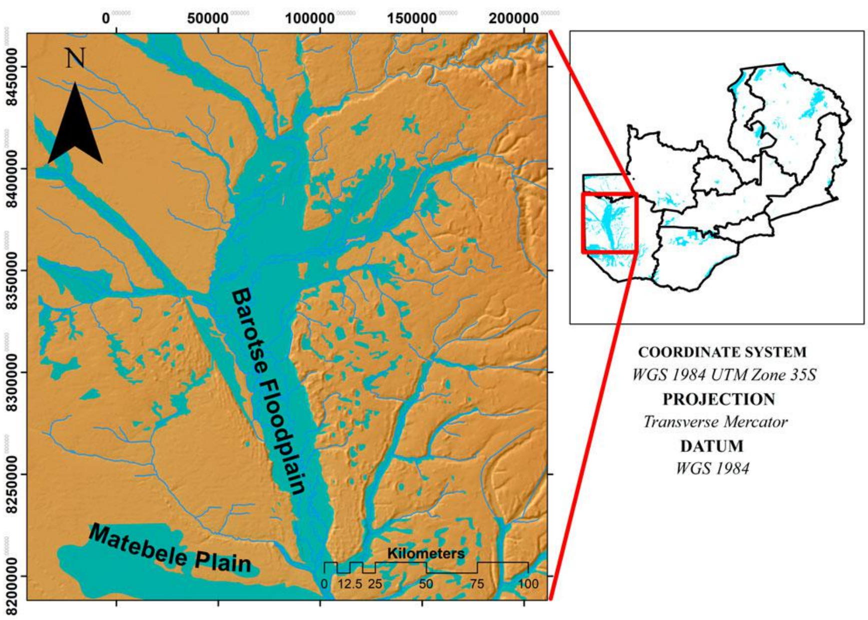

Figure 1: Location of the Barotse Floodplain in the western part of Zambia.

Study location

The Barotse Floodplain is found within the Upper Zambezi Basin (UZB). The basin lies between latitudes 11°S and 19°S, and longitudes 18°E and 27°E, which covers part of western Zambia (Fig. 1). The floodplain measures approximately 240 km long and 34 km wide. According to Turpie et al. (1999), the total wetland area is estimated at 1.2 million hectares.

Methods

In this study, surface water quality and stream sediments of the Barotse Floodplain were characterised during low and high flows. Water samples were collected across the floodplain and tested for their physical, bacteriological, and chemical characteristics. These samples were collected in triplicate at each point and preserved for different laboratory analyses: one sample for anion analysis, another for cation analysis, and the third for bacteriological analysis. Two percent (2%) of 250 ml of nitric acid was added to water samples meant for cation analysis. Acidification of water samples preserved most trace metals and reduced precipitation, microbial activity, and sorption losses to container walls. Bacteriological samples were taken in glass bottles whereas physiochemical samples were stored in plastic bottles. The principal method used for bacteriological analysis was the membrane filtration (MF) method.

Before the collection of water samples, the bottles were rinsed three times together with their respective lids. The depth at which the samples were collected was approximately 50 cm from the water surface, and the same water was used for rinsing. The samples were immediately put into cooler boxes containing ice packs upon completing the collection protocols at each site. In addition, in situ measurements were simultaneously conducted using multi-metres. Multi-metres measured the following physical parameters: dissolved oxygen (DO), temperature, electrical conductivity (EC), and pH. The samples preserved for laboratory analyses were transported to the University of Zambia within 48 hours. A record of each sampled site was created by taking photographs and geographical coordinates. The latter were also used to plot the sampling points using ArcGIS.

Stream sediment samples were collected alongside water quality samples. These two sample types were mostly collected at the same locations. Where it was not practical to collect them at the same water quality locations, an alternative site was chosen within a few metres. These samples were collected using a perforated scoop. They were immediately closed in sampling bottles and placed into the cooler boxes for soil samples. Stream sediments were tested only for their chemical elements using atom atomic absorption spectophotometry (AS) or X-ray fluorescence (XRF). The data presented in this paper were collected over a two-year field campaign: during the wet (April to June) and dry (September to October) seasons of 2014 and 2015. A summary of the methods used is given in Figure 2.

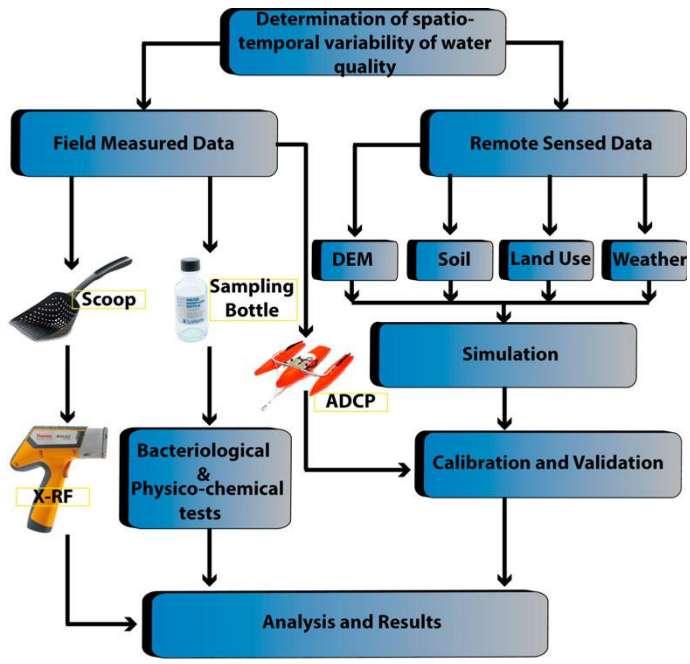

Figure 2: A flow chart illustrating the methods used in this study, which included use of the Acoustic Doppler Current Profiler (ADCP), X-ray fluorescence (X-RF), and remote sensing.

As shown in Figure 2, two types of datasets were used: (1) field-measured data and (2) remote sensing data. Field-measured data were water and stream sediment samples, which were collected using sampling bottles and the scoop, respectively. Elemental constituents in the riverbed sediments were measured to compare with what was in the water. Collected remote sensing data were used for land cover classification and as input into the Soil Water and Assessment Tool (SWAT) model. The model was used to estimate hydrological flows and sediment yields. It was calibrated with stream discharge, which was measured using the acoustic Doppler current profiler (ADCP) (Fig. 2). Land cover change was estimated from supervised classification of Landsat satellite imagery between 1984 and 2015.

Results

In this paper, the results of our findings are presented using representative spatial distribution of sampling points from which (1) bacteriological and physical parameters, (2) variability of agricultural nutrients, (3) heavy metals, (4) non-heavy metals and anions, and (5) sediment yields are described and interpreted.

Representativeness and spatial distribution of sampling points

Sampling points were selected around the Barotse Floodplain (Fig. 3). The basic element of the approach was to characterise water quality parameters from the perspective of transects: (1) Mongu-Kalabo from the Mulambwa Harbour in Mongu to the Luanginga River Harbour in Kalabo Town, (2) Mongu-Lukulu on the northern part of the main Zambezi River to Lukulu, (3) Mongu-Senanga on the eastern side of central floodplain (main Zambezi River) to Senanga, and (4) the Sioma-Kalabo on the western side of the central floodplain (main Zambezi River) from Sioma through the Matebele Plain to Kalabo. Samples were also taken in the middle of the main Zambezi River channel from Mongu to Senanga. The distribution of these points is shown in Figure 3.

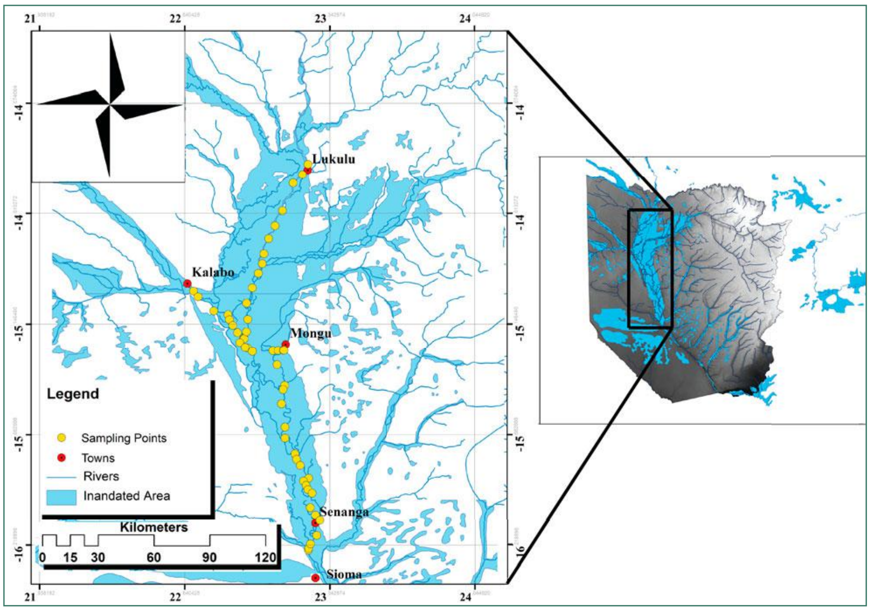

Figure 3: Spatial distribution of sampling points in the Barotse Floodplain, western Zambia.

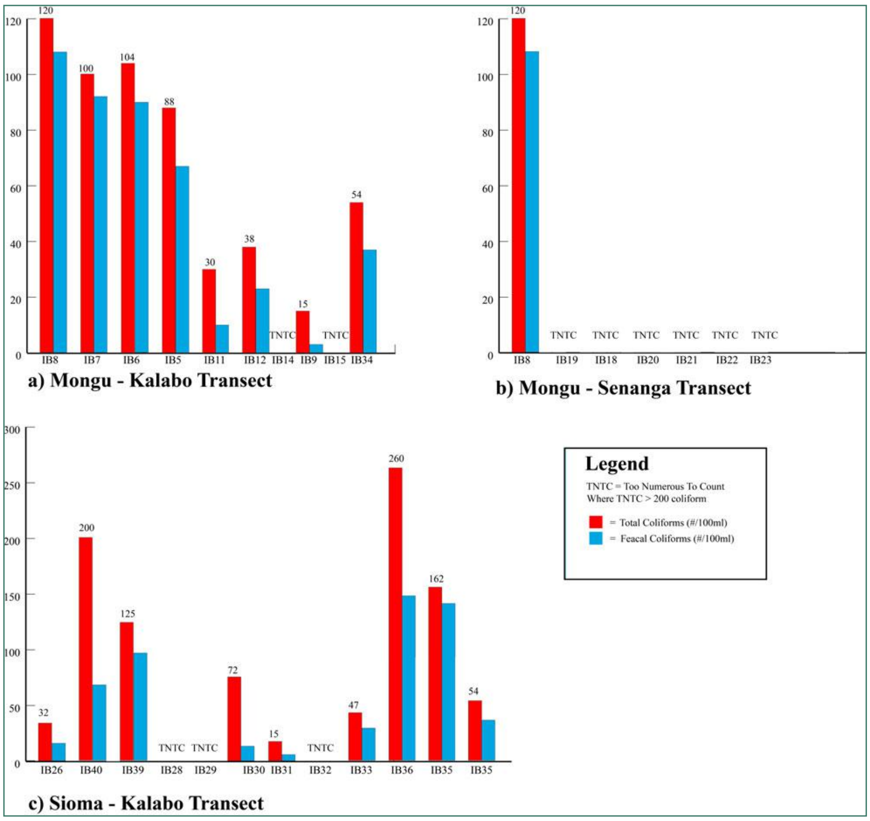

Figure 4: Faecal and total coliform distribution along (a) Mongu-Kalabo transect, (b) Mongu-Senanga transect, and (c) Sioma-Kalabo transects for the 2014 wet-season field campaign in the Barotse Floodplain, western Zambia.

A total of 124 surface water samples were collected for physical, chemical, and bacteriological analysis. Another set of 124 stream sediment samples were also collected. Water and stream sediment samples were taken at the same or nearly the same location depending on the practical feasibility presented at each location.

Bacteriological and physical parameters

Results indicate that faecal and total coliforms were too numerous to count (TNTC) at many sampling points (Fig. 4). In this study, both total and faecal coliforms were considered TNTC if the number of coliforms in a 100 ml sample exceeded 200. The observed high concentrations of these bacteriological indicators were not surprising, as most of these areas were associated with increased anthropogenic activities. For instance, along the Mongu-Senanga transect, human activities such as livestock rearing, sawmilling, open defecation, and sewerage disposal into the streams were identified as being sources of water contamination. The hot spots along this transect were found to be at Sianda stream (IB 18), Sefula Rice Irrigation Scheme (IB 19), Litoya Bridge (IB 20), Mapungu flood area (IB 22), and a sewerage disposal site (IB 23) from the Senanga Secondary School sewer line. Similarly, coliforms were TNTC at sampling points on the Sioma-Kalabo and Mongu-Kalabo transects, which are affected by human activities. The hot spots on the former transect included places where human beings obtained water for their domestic uses. It was also observed that in some cases animals (mainly cattle) also accessed these same points or adjacent areas when meeting their drinking requirements. These were found at Nakatwalenge Basic School (IB 28), Sinungu Basic School (IB 31), and Sikana Basic School (IB 32). The hot spot location on this last transect was found at Mongu Habour (IB 15).

Physical parameters of temperature and DO at all the sampling points in the Barotse Floodplain were also analysed. It was found that the DO was lowest (1.24 mg/l) at Sinungu Basic School (IB 31). This is attributed to animal manure, which is used as fertiliser in the gardens nearby. On the other hand, DO was highest (7.62 mg/l) at Sesheke-Senanga Bridge (IB 25) because of the absence of anthropogenic materials that deplete DO. The temperature was nearly constant from Matongo Hydrometric Station (IB 1) to a stream locally known as Charleton (Jauteni) in Limulunga (IB 17) and then fluctuated after this point (Fig. 5).

Variability of agricultural nutrients

Among the agricultural nutrients, nitrate was found to be relatively higher, particularly in the 2014 wet season (Fig. 6), which experienced higher floods than the 2015 wet season. Others such as total

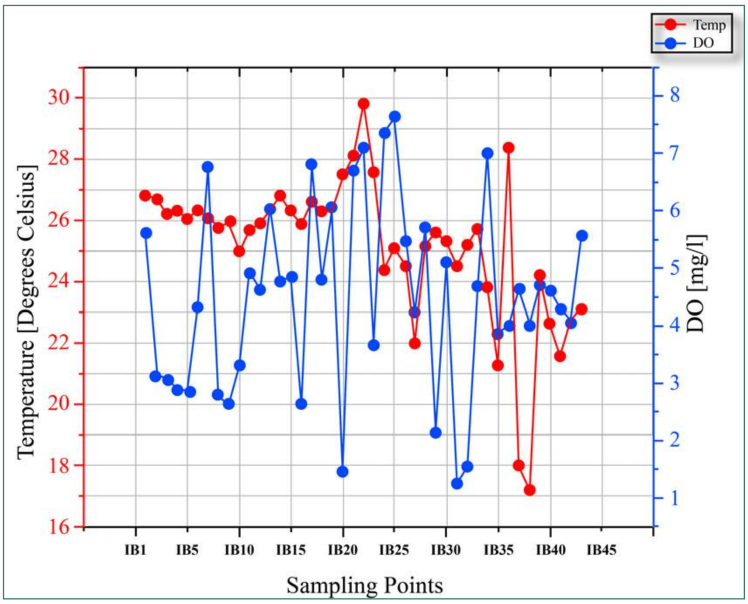

Figure 5: Dissolved oxygen (DO) and temperature variation at different sampling points in the Barotse Floodplain, Western Zambia

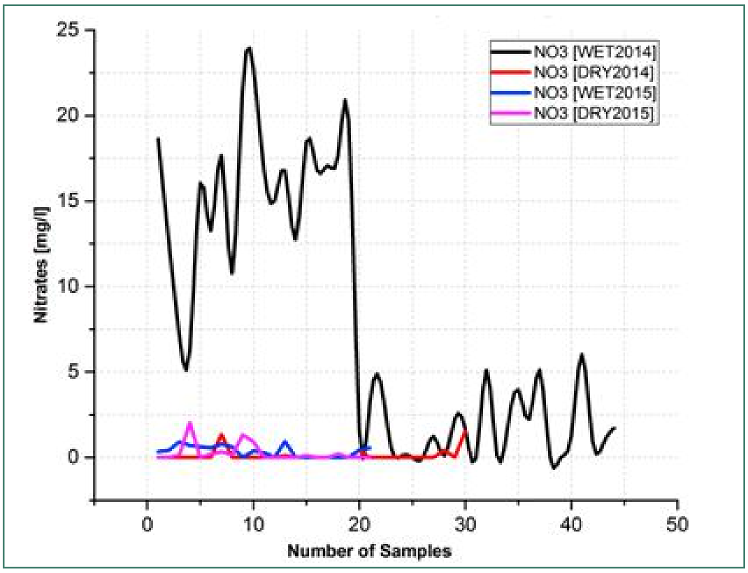

Figure 6: Seasonal values of nitrate concentration in water along the Mongu-Kalabo transect in the wet and dry seasons of 2014 and 2015, Barotse Floodplain, western Zambia.

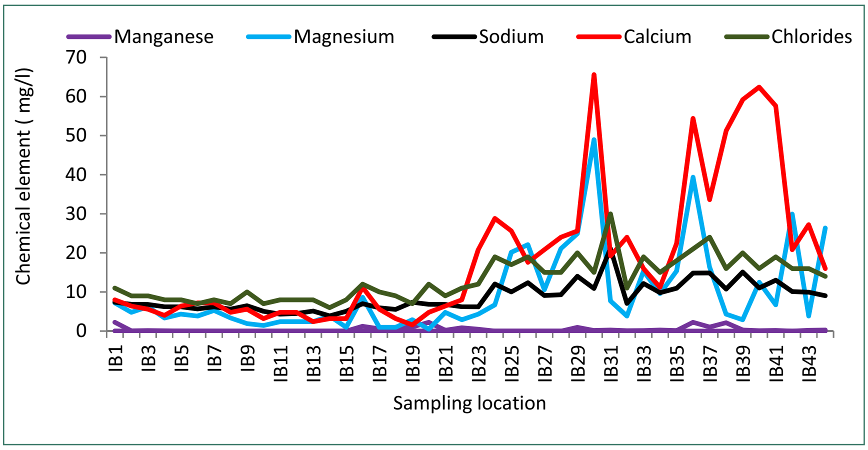

Figure 7: Variation of some non-heavy metals and the anion of chloride at sampling points in the Barotse Floodplain, western Zambia.

phosphates (< 0.01 mg/l) and nitrites (< 0.001 mg/l) were found to be negligible in concentration. From these results, nitrates were considered to be the highest main nutrient supporting the growth of agricultural crops such as maize and vegetables grown in the Barotse Floodplain. Figure 6 also suggests that nitrate nutrients are significantly mobilised and replenished during higher flood seasons.

The source of the nitrate was suspected to be agriculture-related activities around the floodplain. For instance, the local people (mainly Lozi) keep a lot of cattle within the floodplain during the dry season and also practice a complex flood agriculture system. The animals are moved to the highlands and margins of the floodplain during the wet season. It was noted that the year 2014 experienced higher flood levels than 2015. The observed higher concentration of nitrates shown in Figure 6 was therefore attributed to increased mobilisation and recruitment of this element from anthropogenic sources during the higher floods of 2014, whereas in 2015 the source was restricted to small areas around the floodplain.

Heavy metals

On the environmental impact of upstream large-scale mining, particularly in the Kabombo River Basin of north-western Zambia — a tributary of the Zambezi River upstream from the Barotse Floodplain — it was found that concentrations of heavy metals (i.e., copper, lead, cadmium, mercury, arsenic, zinc, and chromium) were negligible (< 0.002 mg/l) and within the World Health Organization (WHO) and Zambia Bureau of Standards (ZABS) standards for potable water in both the water and stream sediment samples. This indicates that water quality within the floodplain is still in its natural state in relation to mining contaminants.

Non-heavy metals and anions

It was instead the concentrations of anions of chlorides, and cations of calcium, magnesium, and sodium that were found to be relatively high in the water samples (Fig. 7).

The relatively elevated levels of concentrations of these elements (Fig. 7) were attributed to a number of factors and processes. For instance, levels of sodium and chloride, which lead to salty water, were found to be high in isolated ponds. These form salt pans as a result of the high rates of evaporation during the dry season. An example of such a feature is the Sisima salt pan, located on the Matebele Plain. One of the water quality samples [Sisima Salt Pond (IB 37)] was taken from this location and contained some of the highest amounts of sodium and chloride (Fig. 7). These elements were also found to be high in places where intensive anthropogenic activities such as gardening were taking place [e.g., Sinungu Basic School (IB 31)]. High concentrations of magnesium were associated with the presence of organic materials and animal waste at some sampling locations [e.g., Libuba Stream at Nambwae Basic School (IB 30)]. It was also suspected, however, that geogenic factors could be influencing high concentrations of magnesium. For instance, a high concentration of magnesium was found in one of the samples [Lukona Basic School (IB 36)], which was taken from a borehole. Seasonal trend analysis of these elements was carried out to understand their variability. In this paper, however, we present such an analysis using calcium, which was frequently the most abundant element in both water and stream sediments.

The trends in calcium concentration on the Mongu-Senanga transect indicated that the medians were Q_{2wet} = 5.2 mg/l and Q_{2dry} = 2.6 mg/l for the wet and dry seasons of 2014, respectively, and Q_{2wet} = 14.4 mg/l and Q_{2dry} = 13.3 mg/l for the wet and dry seasons of 2015, respectively. This transect indicted a positive skewness for both seasons — that is, $Q_3 - Q_2 > Q_2 - Q_1$, or mode < median < mean (Fig. 8), where Q stands for quartiles — that is, upper (Q_3), median (Q2), and lower quartiles (Q_1).

It was observed that there was a considerable increase in calcium concentration from the 2014 wet season to the 2015 wet season. Similar trends were observed from the 2014 dry season to the 2015 dry season. However, there was a general decrease in calcium concentration for seasonal changes within the years (Tab. 1).

The observed seasonal changes in calcium concentration were attributed to complex factors such as variations in the flow regimes between the wet and the dry seasons, and plant uptake of calcium. For instance, calcium is brought into the floodplain system through overland flows and is used up by plants in the formation of new tissues such as roots and shoots. Furthermore, the seasonal variation of calcium was also attributed to changes in the physical parameters of the water, particularly pH. Lower pH favours the dissolution of calcium. It was noted that the pH was mostly lower than 6.9 along the Mongu-Senanga transect (Fig. 9) during the low flows (i.e., dry season) of 2015, which coincided with a period when the concentration of calcium was high (~15mg/l).

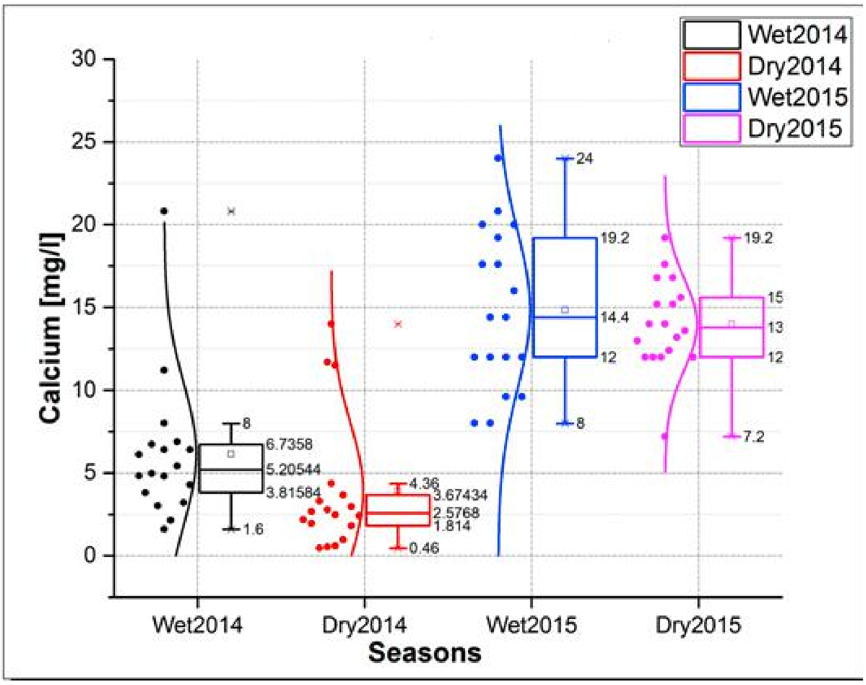

Figure 8: Box plot distribution of calcium concentration on the Mongu-Senanga transect (main Zambezi River) for the wet and dry seasons of 2014 and 2015.

Table 1: Percentage changes in calcium concentration on the Mongu-Senanga transect based on 2014 and 2015 yearly changes (Δ) as well as within-the-year seasonal changes (Δ).

Mongu-Senanga Transect				
2014 Wet Season		*2015 Wet Season*		*Yearly % Δ*
Q_3	6.7	Q_3	19.2	+185.0%
Q_2	5.2	Q_2	14.4	+176.6%
Q_1	3.8	Q_1	12	+214.5%
2014 Dry Season		*2015 Dry Season*		
Q_3	3.7	Q_3	15	+308.2%
Q_2	2.6	Q_2	13	+404.5%
Q_1	1.8	Q_1	12	+561.5%
Seasonal %Δ 2014	−45.5% −50.5% −52.5%	Seasonal %Δ 2015	−21.9% −9.7% 0.0%	

The spatially distributed pH values in Figure 9 were generated using kriging, a geostatistical technique in ArcGIS. Assessment of the predictive accuracy of the technique indicated that the mean square error (MSE) was 0.22 and 0.20 during the low and high flow periods, respectively.

Sediment yields and physical water quality parameters

It was found that the sub-basins within the main floodplain experienced high rates of sedimentation (Fig. 10) as generated by the Soil and Water Assessment Tool (SWAT).

The spatial locations of the hot spot areas where sedimentation is high within

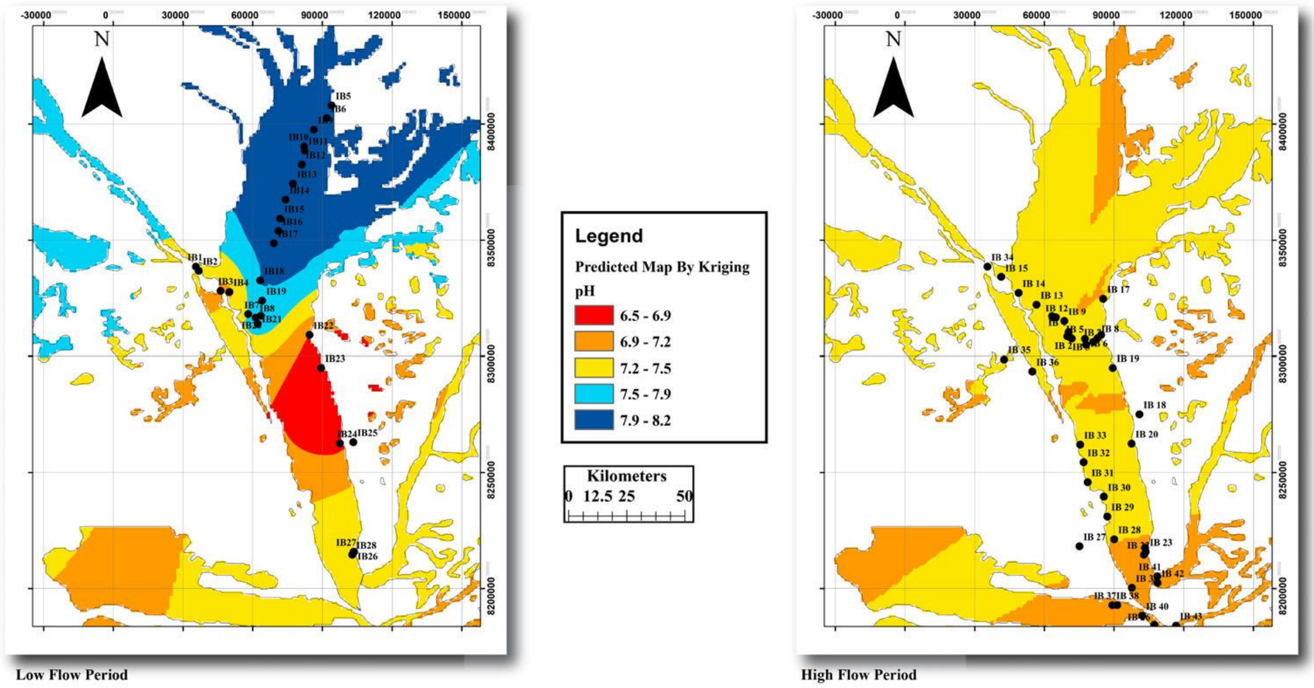

Figure 9: Spatially modelled pH distribution in the dry and wet seasons, Barotse Floodplain, western Zambia.

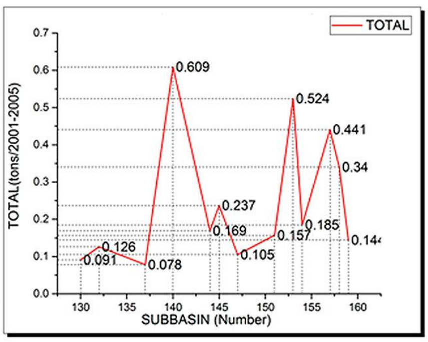

Figure 10: SWAT-estimated sediment accumulation for the years 2001 to 2005 for the sub-basins falling within the Barotse Floodplain.

the floodplain are shown in Figure 11. These areas (coloured brown) are sub-basins 140, 153, 157, and 158. Sub- basin 158 hosts the rice fields at Sefula Irrigation Scheme. The high rate of sediment accumulation has led to frequent clogging of irrigation channels in these fields.

The potential cause of increased sedimentation in the floodplain was attributed to land cover changes as forested land was turned in agricultural land. A study by Zimba et al. (2018), which was conducted within the same broader framework (i.e., SASCCAL Task 191: Developing a water quality and quantity database for western Zambia) as the present work, found that between 1984 and 2015, forest cover declined by about 10%, which translates to an annual reduction rate of about 0.3% (Fig. 12). Since the soil type in the area is sandy in nature, minor changes in forest cover can lead to high rates of sedimentation and an overall change in water quality. Furthermore, conversion of forest to agricultural land and other uses was suspected to be another source of nutrients that enrich the floodplain in the wet season.

Further analysis was done on the water quality samples. This analysis was on the total solids (TS), which is a sum of total suspended solids (TSS) and total dissolved solids (TDS). This calculation was done to infer the conveyance of sediment within the floodwaters. Results (Fig. 13) show that the Mongu-Kalabo transect has more TS being transported during the wet season (April 2014) than

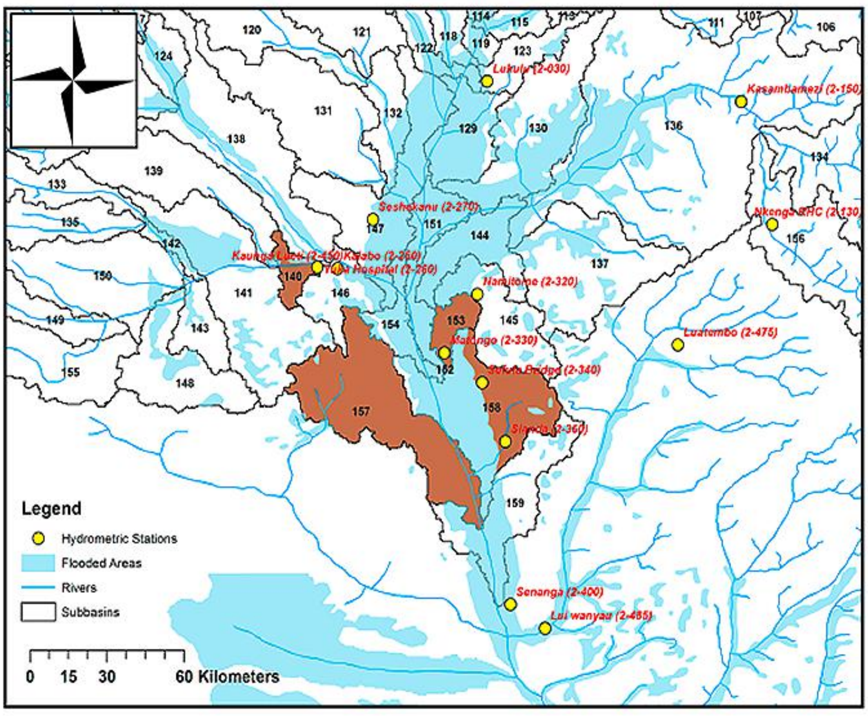

Figure 11: Spatial visualisation of the sub-basins highly impacted by sedimentation (brown-coloured areas), as simulated by the SWAT model.

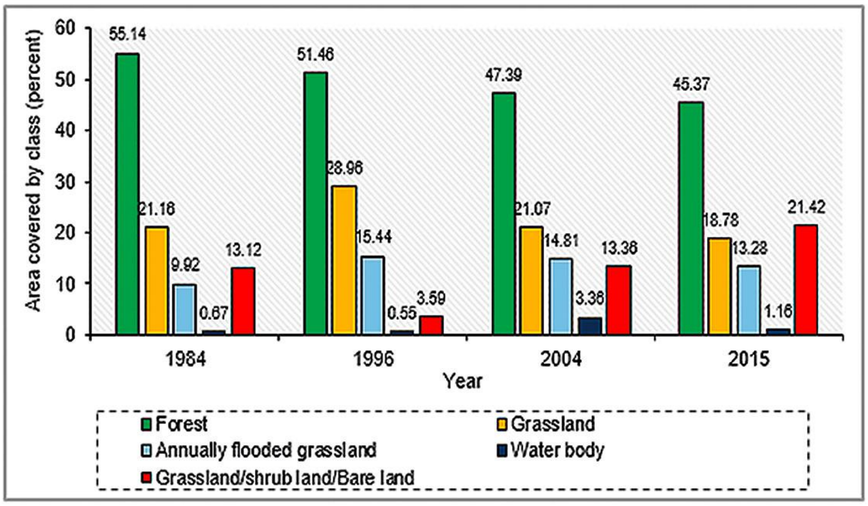

Figure 12: Land cover change between 1984 and 2015 in the Barotse sub-basin, western Zambia (Zimba et al., 2018).

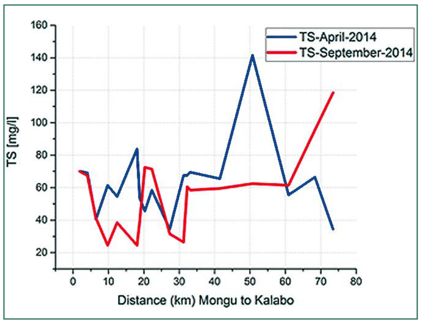

Figure 13: Variation of TS concentration in the wet and dry seasons of 2014 along the Mongu-Kalabo transect.

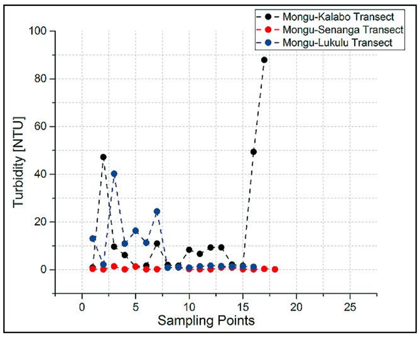

Figure 14: Turbidity in the Luanginga River (Mongu–Kalabo transect) and main Zambezi River (Mongu-Lukulu transect) compared to main Zambezi River along the Mongu-Senanga transect.

in the dry season (September 2014) emanating from the Luanginga River to the Zambezi River. Similar trends were observed along the other transects, particularly from Lukulu to Mongu and Mongu to Senanga.

It was observed that turbidity was high in the Luanginga River (Mongu-Kalabo transect) and main Zambezi River (Mongu-Lukulu transect). This was attributed to the huge amount of sediment that is recruited as water from various tributary streams confluence upstream from these rivers. Within the main floodplain, however, vegetation acts like a porous barrier, forcing the sediments to be deposited on the riverbanks and sieving out some of the sediments. This process was assumed to be responsible for finally reducing turbidity within and after the floodplain along the Mongu-Senanga transect (Fig. 14).

Discussion

The variations in the chemical elements in the floodplain were noted to be closely linked to flood inundation patterns. This trend included high nitrate and calcium concentrations attributed to recruitment occurring during higher floods. These findings are in agreement with previous studies conducted in the same area. For instance, Zurbrügg (2012), who studied the biogeochemistry of the Barotse Floodplain and the dam-impacted Kafue Wetland, observed a high seasonal variability in calcium concentration. Similarly, Zuijdgeest et al. (2015) found high concentrations of nitrate in the flood season in the Barotse Floodplain. They also observed that other agricultural nutrients such as phosphorus were largely close to the limit of detection. It should be noted, however, that the aforementioned studies did not attribute the variability of these elements to any particular processes. Nevertheless, our hypothesis that the variability of elements is associated with flooding patterns is reasonably supported by numerous studies on fundamental processes of wetland functions. For instance, it has been shown (e.g., Sinkala et al., 2002) that the variability of elements in a wetland is part of natural processes that serve to maintain the unique ecological functions of these water bodies. Schot & Wassen (1993) noted that floodplains tend to have dense vegetation during the wet season, as the available calcium supports tissue development.

The observed low levels of mining-related element concentration suggested that the water quality of the floodplain is not yet under threat from the mining sources of contamination in the northern part of the basin. Zuijdgeest et al. (2015) noted that the Kafue Flats and the Barotse Floodplain differ in anthropogenic influence and considered the latter to be pristine in large parts. This view was also upheld by other researchers such as Zurbrügg (2012) and Nyoni (2014).

Anthropogenic economic activities (e.g., farming, wetland grazing, and deforestation) within the floodplain seem to be the major predicators of biophysical water parameters. It was noted that sampling points near settled areas registered high peaks of bacteriological contamination. Since the Barotse Floodplain is a major source of livelihood for the local people, it is expected that such anthropogenic pollution will increase with population growth. An increase in population means that a significant part of the floodplain will be overexploited for its rich resources, which include fertile soils, fauna, and flora. For instance, sedimentation in some of the locations (e.g., Sefula Rice Scheme) was found to be significantly high and was attributed to increased conversion of forest to agricultural land. The number of people settling in the floodplain has since been increasing steadily. Mutonga (2013) has also noted that sedimentation in the Barotse Floodplain will likely increase with population growth and that unpredictable floods arising from climate variability will exacerbate diseases and hunger because of the destruction of crops.

Although anthropogenic activities were noted to have adverse effects on biophysical water quality, evidence also suggests that this was part of seasonal trends. For instance, low dissolved oxygen and high bacteriological contamination were observed in non-settled areas during the low flows or dry season. These trends were also noted by Nyoni (2014). This implies that the system 'cleanses' itself during high-flow periods. Similarly, certain diseases such as malaria that were found to be predominant during low flows were very low during high flow periods (Banda et al., 2015). This is because stagnant water during the dry season creates a conducive environment for microbiological organisms to replicate as flood levels regress.

Conclusion

This study was aimed at assessing the determinants of spatio-temporal variations in selected water quality parameters in the Barotse Floodplain. These included bacteriological and physiochemical parameters. All of these parameters varied significantly across the study area and over time (i.e., wet and dry seasons). Drivers of these changes are attributed to both anthropogenic and natural processes. Increased activities such as deforestation and agricultural production around this critical water resource were related to high nutrient loading, low DO, and bacteriological contamination of water, especially in settled water courses. Sedimentation was also observed to be on the increase as the result of these activities. Future economic pressures in and around the floodplain are likely to exacerbate this scenario. On the other hand, the change in water quality parameters was also related to natural processes such as low and high flooding patterns. These processes are critical in the 'renewal' of biogeochemical processes and ecological balance of the floodplain. For instance, high recruitment of some elements (e.g., calcium and nitrate) occurred in the wet season. This process serves many functions, including replenishing nutrients in the soils, that have been sustaining flood agriculture among the local people in the Barotse Floodplain for decades. It is therefore important that this balance be maintained and that the system not become overloaded by economic activities. Despite current baseline data indicating that the Barotse Floodplain is still in a pristine state, continuous monitoring is encouraged because of upstream large-scale copper mining, increased population in the area, and resulting increased anthropogenic activities.

Recommendations

The study recommends to relevant institutions and stakeholders that:

- water quality sampling should continue to be done seasonally by the Water Resources Management Authority (WARMA) in light of increased economic activities around and upstream of the floodplain;
- development of a plan to halt deforestation in the catchments surrounding the floodplain should be done urgently by the Forestry Department in the Ministry of Lands and Natural Resources working together with the Ministry of Agriculture and Livestock to reduce sedimentation and overall poor water quality; and
- the Zambia Environmental Management Agency (ZEMA), working together with WARMA, should focus on water pollution plans to halt any incoming heavy metal pollution from the large-scale copper mining upstream in Zambia's Northwestern Province.

Acknowledgements

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References

Ahiablame, L., Chaubey, I. & Smith, D. (2010) Nutrient content at the sediment-water interface of tile-fed agricultural drainage ditches. *Purdue University Department of Earth, Atmospheric, and Planetary Sciences Faculty Publications*, **2**, 411–428.

Banda, S., Namafe C.M. & Chakanika, W.W. (2015) Traditional environmental knowledge among Lozi adults in mitigating climate change in the Barotse Plains of western Zambia. *International Journal of Humanities, Social Sciences, and Education*, **2**, 89–108.

Bilotta, G.S. & Brazier, R.E. (2008) Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research*, **42**, 2849–2861.

Gregory, S.V., Swanson, F.J., McKee, W.A. & Cummins, K.W. (1991) An ecosystem perspective of riparian zones. *Bio-Science*, **41**, 540–551.

Lovett, S., Price, P. & Edgar, B. (2007) *Salt, nutrient, sediment and interactions. Findings from the National River Contaminants Program.* Land & Water Australia, Canberra.

Mutonga, M. (2013) *An ethical assessment of human adaptation to annual floods in Mongu's Barotse Floodplains and its impact on environment.* Master's thesis, University of Zambia, Lusaka, Zambia.

Naiman, R.J. & Décamps, H. (1997) The ecology of interfaces — riparian zones. *Annual Review of Ecology and Systematics*, **28**, 621–658.

Naiman, R.J., Décamps, H. & McClain, M. (2005) *Riparia: ecology, conservation and management of streamside communities.* Elsevier, San Diego, CA, USA.

Noe, G.B. & Hupp, C.R. (2007) Seasonal variation in nutrient retention during inundation of a short-hydroperiod floodplain. *River Research and Applications*, **23**, 1088–1101.

Nyoni, F.C. (2014) *Carbon dynamics in two river systems in Zambia: a comparative study of the Zambezi and the Kafue Rivers.* Master's thesis, University of Zambia, Lusaka, Zambia.

Polunin, V.C.N (2014) *Aquatic ecosystems: trends and global prospects.* Cambridge University Press, Cambridge, UK.

Schot, P.P. & Wassen, M.J. (1993) Calcium concentrations in wetland groundwater in relation to water sources and soil conditions in the recharge area. *Journal of Hydrology*, **141**, 197–217.

Sinkala, T., Mwase, E.T. & Mwala, M. (2002) Control of aquatic weeds through pollutant reduction and weed utilization: a weed management approach in the lower Kafue River of Zambia. *Physics and Chemistry of the Earth*, **27**, 983–991.

Tockner, K. & Stanford, J.A. (2002) Riverine flood plains: present state and future trends. *Environmental Conservation*, **29**, 308–330.

Tong, S.T.Y. & Chen, W. (2002) Modeling the relationship between land use and surface water quality. *Journal of Environmental Management*, **66**, 377–393.

Turpie, J., Smith, B., Emerton, L. & Barnes, J. (1999) *Economic value of the Zambezi basin wetlands.* Zambezi Basin Wetlands Conservation and Resource Utilization Project, IUCN Regional Office for Southern Africa, The Canadian International Development Agency (CIDA), University of Cape Town, Cape Town, South Africa.

Zimba, H., Banda, K., Chabala, A., Phiri, W., Selma, P., Meinhardt, M. & Nyambe, I. (2018) Assessment of trends in inundation extent in the Barotse Floodplain, upper Zambezi River Basin: A remote sensing approach. *Journal of Hydrology: Regional Studies*, **15**, 149–170.

Zuijdgeest, A.L., Zurbrugg, R., Blank, N., Fulcri, R., Senn, D.B. & Wehrli, B. (2015) Seasonal dynamics of carbon and nutrients from two contrasting tropical floodplain systems in the Zambezi River basin. *Biogeosciences*, **12**, 7535–7547.

Zurbrügg, R., 2012. *Biogeochemistry of a large tropical floodplain system (Kafue Flats, Zambia): river-floodplain exchange and dam impacts*. PhD dissertation (DISS. ETH No. 20309), ETH Zürich, Switzerland.

References [CrossRef]

Ahiablame, L., Chaubey, I. & Smith, D. (2010) Nutrient content at the sediment-water interface of tile-fed agricultural drainage ditches. *Purdue University Department of Earth, Atmospheric, and Planetary Sciences Faculty Publications*, **2**, 411–428. CrossRef

Banda, S., Namafe C.M. & Chakanika, W.W. (2015) Traditional environmental knowledge among Lozi adults in mitigating climate change in the Barotse Plains of western Zambia. *International Journal of Humanities, Social Sciences, and Education*, **2**, 89–108.

Bilotta, G.S. & Brazier, R.E. (2008) Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research*, **42**, 2849–2861. CrossRef

Gregory, S.V., Swanson, F.J., McKee, W.A. & Cummins, K.W. (1991) An ecosystem perspective of riparian zones. *Bio-Science*, **41**, 540–551. CrossRef

Lovett, S., Price, P. & Edgar, B. (2007) *Salt, nutrient, sediment and interactions. Findings from the National River Contaminants Program.* Land & Water Australia, Canberra.

Mutonga, M. (2013) *An ethical assessment of human adaptation to annual floods in Mongu's Barotse Floodplains and its impact on environment*. Master's thesis, University of Zambia, Lusaka, Zambia.

Naiman, R.J. & Décamps, H. (1997) The ecology of interfaces — riparian zones. *Annual Review of Ecology and Systematics*, **28**, 621–658. CrossRef

Naiman, R.J., Décamps, H. & McClain, M. (2005) *Riparia: ecology, conservation and management of streamside communities.* Elsevier, San Diego, CA, USA.

Noe, G.B. & Hupp, C.R. (2007) Seasonal variation in nutrient retention during inundation of a short-hydroperiod floodplain. *River Research and Applications*, **23**, 1088–1101. CrossRef

Nyoni, F.C. (2014) *Carbon dynamics in two river systems in Zambia: a comparative study of the Zambezi and the Kafue Rivers.* Master's thesis, University of Zambia, Lusaka, Zambia.

Polunin, V.C.N (2014) *Aquatic ecosystems: trends and global prospects.* Cambridge University Press, Cambridge, UK.

Schot, P.P. & Wassen, M.J. (1993) Calcium concentrations in wetland groundwater in relation to water sources and soil conditions in the recharge area. *Journal of Hydrology*, **141**, 197–217. CrossRef

Sinkala, T., Mwase, E.T. & Mwala, M. (2002) Control of aquatic weeds through pollutant reduction and weed utilization: a weed management approach in the lower Kafue River of Zambia. *Physics and Chemistry of the Earth*, **27**, 983–991. CrossRef

Tockner, K. & Stanford, J.A. (2002) Riverine flood plains: present state and future trends. *Environmental Conservation*, **29**, 308–330. CrossRef

Tong, S.T.Y. & Chen, W. (2002) Modeling the relationship between land use and surface water quality. *Journal of Environmental Management*, **66**, 377–393. CrossRef

Turpie, J., Smith, B., Emerton, L. & Barnes, J. (1999) *Economic value of the Zambezi basin wetlands.* Zambezi Basin Wetlands Conservation and Resource Utilization Project, IUCN Regional Office for Southern Africa, The Canadian International Development Agency (CIDA), University of Cape Town, Cape Town, South Africa.

Zimba, H., Banda, K., Chabala, A., Phiri, W., Selma, P., Meinhardt, M. & Nyambe, I. (2018) Earth observation assessment of wetland inundation extent variations in the Barotse wetland, Upper Zambezi basin using Desert Flood Index. *Journal of Hydrology: Regional Studies*, **15**, 149–170.

Zuijdgeest, A.L., Zurbrugg, R., Blank, N., Fulcri, R., Senn, D.B. & Wehrli, B. (2015) Seasonal dynamics of carbon and nutrients from two contrasting tropical floodplain systems in the Zambezi River basin. *Biogeosciences*, **12**, 7535–7547. CrossRef

Zurbrügg, R., 2012. *Biogeochemistry of a large tropical floodplain system (Kafue Flats, Zambia): river-floodplain exchange and dam impacts*. PhD dissertation (DISS. ETH No. 20309), ETH Zürich, Switzerland.

Water resources

Monitoring water quality of the Upper Okavango Delta

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Abstract: The water quality of the Upper Okavango River has been described as pristine for many years since the water chemistry of the system was first studied. However, modern developmental activities and natural environmental processes are now threatening the quality and quantity of this river water. Continuous monitoring is important for providing scientific data that can be used to detect early warning signs of system changes and support effective management and protection of the resource. In this project, water quality of the Upper Okavango delta (Panhandle) was studied continuously from July 2014 to 2017 using physicochemical parameters. Field parameters were measured on-site using calibrated meters, and major ions were analysed in the laboratory using standard methods. Levels of electrical conductivity, pH, dissolved oxygen, and turbidity showed significant differences between sampling sites but still within international freshwater and drinking water guidelines. Statistical analysis showed no significant variations in water quality parameters over the years of the study. Parameters displayed seasonal cyclic variations controlled mainly by temperature (concentrated chemical species in summer) and flood levels (diluted most parameters during high floods). High floods also reduced dissolved oxygen concentration in river waters to a minimum of less than 1 mg/l, concentrations lethal to aquatic organisms, especially fish. This depletion occurred because high floodwaters bring in high levels of organic matter, which has a high oxygen demand for decomposition processes. The ionic composition of the Panhandle waters was found to be dominated by calcium (1.1–32.8 mg/l) and bicarbonate (0.9–77.2 mg/l), but still remained fresh. Although major land use changes are reported in the upper Namibian Kavango area, no apparent impact on water quality has been observed in this study.

Resumo: A qualidade da água na parte superior do Rio Okavango foi descrita como pristina durante muitos anos, desde que a química da água do sistema foi estudada pela primeira vez. Porém, actividades de desenvolvimento modernas e processos ambientais naturais estão agora a ameaçar a qualidade e quantidade desta água fluvial. A monitorização contínua é importante de modo a fornecer dados científicos que possam ser utilizados para detectar sinais de alerta precoces de alterações no sistema e apoiarem a gestão efectiva e protecção do recurso. Neste projecto, a qualidade da água do Delta de Okavango (panhandle) foi estudada continuamente de Julho de 2014 a 2017, com recurso ao uso de parâmetros físico-químicos. Os parâmetros de campo foram medidos no local com aparelhos calibrados, e os iões principais foram analisados no laboratório com recurso a métodos padrão. Os níveis de condutividade eléctica, pH, oxigénio dissolvido e turbidez mostraram diferenças significativas entre os locais amostrados, mas ainda dentro das normas internacionais de água doce e potável. A análise estatística não mostrou variações significativas dos parâmetros de qualidade da água entre os anos de estudo. Os parâmetros exibiram variações cíclicas sazonais, essencialmente controladas pela temperatura (espécies químicas concentradas no Verão) e níveis de inundação (diluição da maioria dos parâmetros nas altas inundações). As grandes inundações reduziram também a concentração de oxigénio dissolvido nas águas fluviais até a um mínimo inferior a 1mg/l, concentrações letais para organismos aquáticos, em especial os peixes. Este empobrecimento ocorreu pois as grandes inundações trazem altos níveis de matéria orgânica que possui uma elevada exigência de oxigêncio para os processos de decomposição. Descobriu-se que a composição iónica das águas do panhandle é dominada por cálcio (1,1 – 32,8 mg/l) e bicarbonato (0,9 – 77,2 mg/l), mas esta mantém-se doce. Apesar de serem relatadas importantes alterações no uso das terras na área superior do Kavango na Namíbia, este estudo não observou nenhum impacto aparente na qualidade da água.

Introduction

Water is a natural resource essential for supporting all forms of life. Rivers, streams, lakes, and other freshwater bodies are used as sources for drinking, irrigation, industrial development, fish and wildlife habitats, and maintenance of ecosystem balance (Carr & Neary, 2008). The value of these water resources in providing for human needs and ecosystem health depends largely on their quantity and quality. The quality of a water body is defined by its physical, chemical, biological, microbiological, and aesthetic properties (Carr & Neary, 2008). There is a need for protection of water resources for sustainable use, and water quality research is critical for providing scientific data to inform policy decisions in water resources management. The Okavango delta in Botswana is an important water source for riparian communities, wildlife, and the national tourism industry (McCarthy & Ellery, 1998). The headwaters of the river are located in Angola, where most of the runoff is generated, and each year rainwater travels through the Cubango and Cuito River system into Namibia, where about 9,200 million m^3 enter the delta (McCarthy & Ellery, 1998). Given its international importance as a Ramsar site and a UNESCO World Heritage site, the Okavango delta has been the subject of several studies aimed at assessing changes in surface water quality for supporting effective management of the resource (Ashton et al., 2003; Mackay et al., 2011; Gondwe & Masamba, 2016; Tubatsi et al., 2014; West et al., 2015). Major ion chemistry of the Okavango was also studied (Masamba & Muzila, 2005; Sawula & Martins, 1991). The conclusion from these studies was that the water quality of the upper delta varied seasonally as a result of natural influences such as temperature changes and annual flooding but that the influence of human activities was not apparent. Because the studies were short-term undertakings, however, no conclusions could be drawn regarding whether the water quality of the Okavango system was changing over time, from year to year. Land use changes in the delta and upstream have the potential to affect the water quality of the Okavango River (Masamba & Mazvimavi, 2008). Large-scale industrialised agriculture and increasing human settlements have been reported in the Namibian Kavango area (Propper et al., 2015). These are likely to increase fertiliser, pesticides, and sediment loadings in the delta and lead to a deterioration of water quality and loss of biodiversity in the Okavango delta. The water quality changes may seem negligible (such as temperature rise resulting from climate change) and be masked by seasonal changes in short-term studies, so long-term studies are critical to reveal real trends. The main objective of this study was to assess spatial-temporal variations in water quality in the Okavango Panhandle over 3 years using physicochemical indicators. These data will provide information on water quality trends with respect to different locations in the Panhandle, seasons, and year-to-year changes.

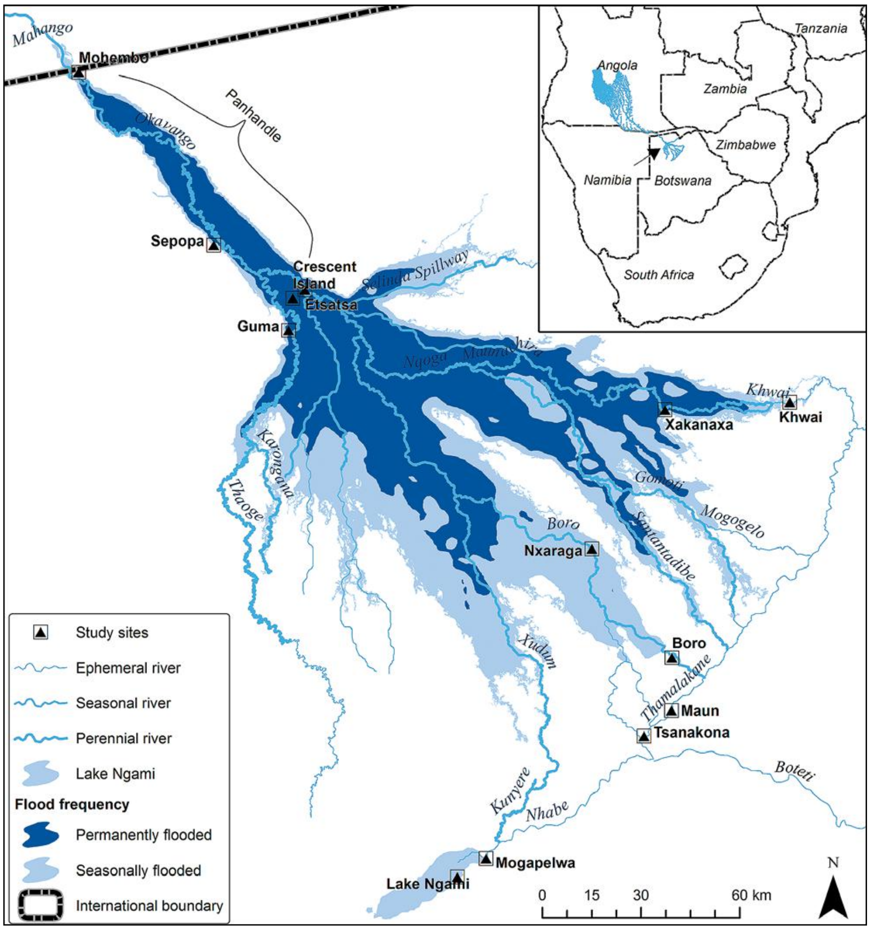

Figure 1: Map showing sampling sites in the Okavango Delta panhandle and lower delta.

Materials and methods

Study site

The Okavango delta occupies an area of about 40,000 km^2 in northern Botswana. It is one of the largest inland delta fans in the world (Gumbricht, 2004) and one of Africa's most pristine wetlands (McCarthy & Ellery, 1998). Annually, the delta receives 6,140 million m3 of water from local rainfall, and an additional 9,200 million m^3 is supplied by Angolan tributaries (Nash et al., 2006). The delta consists of two distinct sections, the Panhandle and the alluvial fan. The Panhandle (Fig. 1), approximately 90 km long and 15 km wide, is the entry corridor to the Okavango delta (McCarthy et al., 2007). It consists mostly of permanent swamps with well-defined deep water channels and seasonal marshes on the fringes of the channels. The water quality monitoring sites for the SASSCAL Task 344 project were spread out to cover most of the delta (Fig. 1) to document the water quality status of the entire area. For the Panhandle, five sampling sites were selected representing the entry point of the river water from Namibia (Mohembo), middle point (Sepopa), side tributary (Etsatsa and Crescent Island), and lower point of the Panhandle (Guma). In the Lower Okavango delta, known as the alluvial/distal fan, eight sampling sites were selected for monitoring (Fig. 1), but only selected results of the Panhandle will be reported in this chapter.

Sampling

Water sampling began in July 2014 and continued to July 2017. Samples were collected monthly in triplicate from each sampling location. The monthly sampling cycles were meant to cover all essential events occurring within the river systems that were likely to influence water quality in the delta, such as seasons and flooding cycles. The international grab sampling protocol for surface waters was followed during sampling. Samples for laboratory analysis were preserved accordingly and transported to the laboratory of the Okavango Research Institute for processing. Discharge values reported here are for Mohembo only and were obtained from the Department of Water Affairs, Botswana, which measures discharge daily at Mohembo and other sites in the delta.

Analysis

Field water quality parameters (electrical conductivity, pH, dissolved oxygen, turbidity, and temperature) were all measured on-site using calibrated field meters. Major ions (calcium, magnesium, potassium, sodium, bicarbonates, chlorides, sulphates) and other parameters were analysed at the laboratory of the Okavango Research Institute in Maun, following protocols provided in the American Public Health Association's *Standard Methods for the Examination of Water and Wastewater, 22nd edition* (Rice et al., 2012).

Data analysis

We used descriptive statistics and one-way analysis of variance (ANOVA) to evaluate similarities and dissimilarities among sampling periods and sampling sites with a significance level at $p \leq 0.05$. Time series plots were used to illustrate the variations of some water quality parameters over the study period.

Results

Field parameters

Although discharge is not a water quality parameter, it is presented here because it was used in this study to determine low and high flood periods (Fig. 1). High floods were considered to occur from January to June, and low floods occurred from July to December. Results of water quality parameters (temperature, pH, electrical conductivity, dissolved oxygen, and turbidity) measured in the Panhandle are given (Tab. 1). The statistical analysis (ANOVA) revealed that all field parameters tested, except temperature, varied significantly among sites ($p < 0.05$). However, the temporal variations were not significant for all field parameters tested.

The highest recorded discharge at Mohembo in the year 2014 was 665 m^3s^{-1}; in 2015, 573 m^3s^{-1}; in 2016, 777 m^3s^{-1}; and in 2017, 445 m^3s^{-1}.

Temperatures in the Panhandle varied across sampling sites and seasons, with a range of 15.7–36.6 °C (Tab. 1). Crescent Island recorded the lowest temperature of 15.7°C at low floods, and the highest of 37.7°C was recorded at Etsatsa, also during a period of low floods. ANOVA revealed that the differences observed among sampling sites and between the flood stages were not significant ($p > 0.05$). Figure 2a illustrates the general cyclic pattern during the study period, the overlaps between the solid line and dotted line revealing close similarity in water temperature between the upper Panhandle (Mohembo) and the lower Panhandle (Guma).

The pH in the Panhandle ranged from 5.2, recorded at Etsatsa, to 7.5, recorded at Crescent Island, indicating acidic waters

Table 1: Mean, minimum, maximum and standard deviation of water quality parameters in the Okavango Panhandle from 2014 to 2017

	Mohembo				Sepopa				Etsatsa				Crescent				Guma			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Low Floods																				
T (°C)	22.4	3.9	16.5	27.6	22.9	4.6	16.2	29.1	22.9	5.2	16.3	36.6	22.4	4.5	15.7	28.6	22.5	4.3	16	28.5
pH	6.7	0.3	6.3	7.2	6.5	0.2	6.0	7.0	6.6	0.4	5.2	7.3	6.5	0.3	5.7	7.5	6.6	0.3	5.8	7.4
EC (µS/cm)	31.5	3.1	27.3	41.8	35.3	4.3	26.6	46.1	37.6	5.7	30.5	53.9	38.6	4.7	28.5	45.9	42.4	8.7	28.7	56.9
DO (mg/L)	6.7	1.4	2.5	8.4	5.3	1.0	2.2	6.7	5.3	1.4	2.4	10	4.2	1.3	1.5	7.1	5.0	1.0	2.3	6.4
Turbidity (NTU)	14.1	3.4	7.3	21.7	9.1	4.8	0.7	16.5	6.7	4.9	0.8	17.6	5.2	3.8	0.4	13.5	1.7	0.7	0.3	3.6
High floods																				
T (°C)	24.7	4.1	17.6	28.7	24.5	4.1	17.1	29.3	24.5	3.7	17.3	29.2	24.4	3.7	17.3	29.3	24.3	3.8	17.5	29.9
pH	6.4	0.3	5.6	6.8	6.3	0.2	5.9	6.8	6.3	0.3	5.7	7.0	6.2	0.3	5.8	6.7	6.3	0.3	6.0	6.9
EC (µS/cm)	37.2	3.8	31.1	43.6	40.7	10.3	30.9	67.7	43.1	14.7	30.4	73	46.9	22.5	30.3	99.8	42.4	11.2	31.5	64.8
DO (mg/L)	5.2	1.9	0.7	8.9	2.6	1.8	0.6	6.8	3.5	2.3	0.6	7.3	2.9	2.3	0.2	6.8	3.8	1.9	0.9	6.6
Turbidity (NTU)	4.8	1.9	3.1	8.8	2.5	1.7	0.3	7.5	3.2	2.7	0.8	8.8	3.7	3.9	0.6	13.5	2.3	0.9	0.7	3.8
Major ions (mg/l)																				
Na	1.7	0.5	ND	3.2	1.9	0.5	0.9	4.1	1.8	0.6	0.1	3.6	2.1	0.9	1.1	5.3	2.0	0.4	1.4	3.1
Ca	3.8	0.7	2.8	7.5	3.9	0.8	3.1	9.1	4.1	1.4	1.1	13.6	4.7	3.7	1.5	32.8	4.9	1.6	2.7	10.5
Mg	1.0	0.2	0.3	1.6	1.1	0.2	0.5	2.0	1.1	0.8	0.8	8.8	1.2	0.4	0.9	3.0	1.3	0.4	0.8	2.4
K	1.4	0.5	ND	3.4	1.4	0.6	ND	4.0	1.3	0.8	ND	4.4	1.8	1.5	ND	7.7	1.2	0.6	ND	2.9
HCO_3	23.2	6.8	4.6	39.8	23.8	14.9	ND	130.6	25.3	10	ND	51.7	24.2	12.4	0.9	50.1	28.3	11.3	3.3	77.2
SO_4	0.5	0.9	ND	8.4	5.2	20.8	ND	120.4	0.3	0.4	ND	1.6	0.4	0.4	ND	2.6	0.6	0.7	ND	5.6
CL	0.4	0.8	ND	7.3	0.9	3.3	ND	19.5	0.6	0.9	ND	3.1	0.4	0.6	ND	2.8	0.1	0.1	ND	1.1

ND = Not detected with the analytical technique used

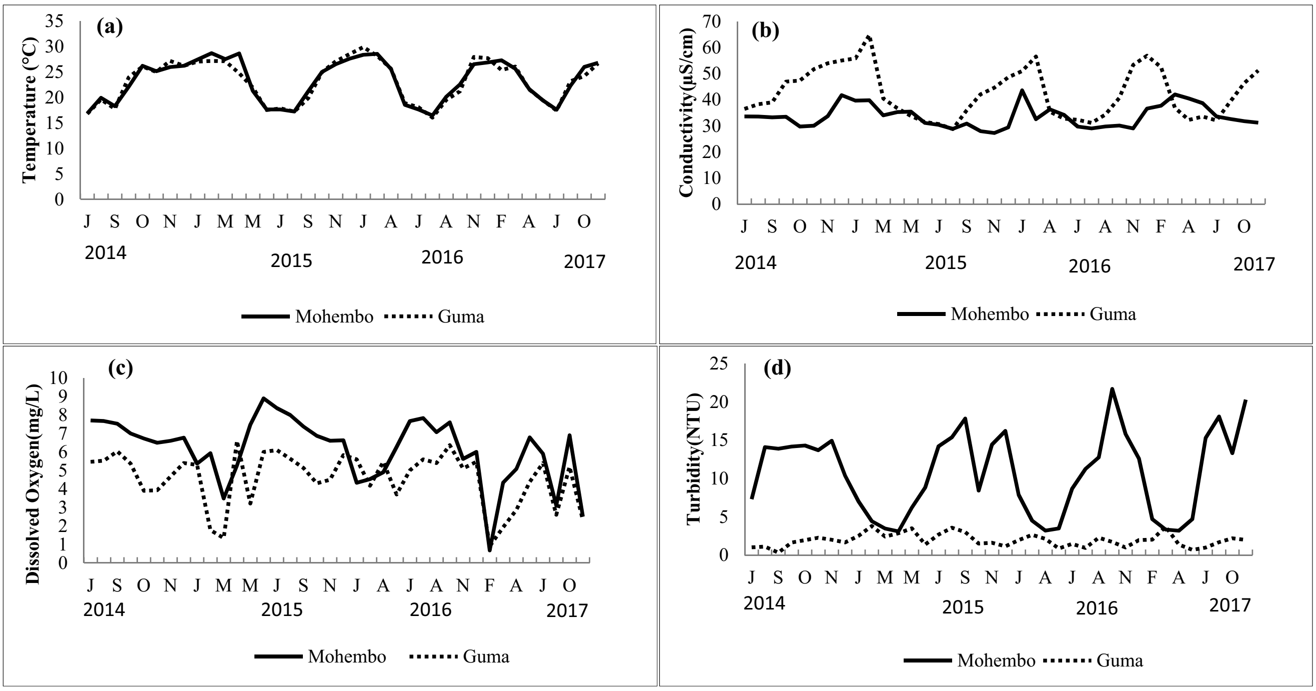

Figure 2: Time series plots for averages (a) temperature (b) conductivity (c) dissolved oxygen (d) turbidity in the Upper (Mohembo) and Lower (Guma) Panhandle

to neutral and even near-alkaline conditions. An ANOVA test revealed that pH varied significantly among the five study sites, with the highest mean at Mohembo and the lowest at Crescent Island. Flood stage influences were observed, as pH was also significantly higher ($p = 0.000$) during low floods than at high floods.

Electrical conductivity is a measure of dissolved salts in a water body. Mohembo recorded the lowest EC of 27.3 µS/cm, and Crescent Island recorded the highest of 99.8 µS/cm (Tab. 1). Although average concentrations at all sampling sites remained relatively low (all below 100 µS/cm), EC increased significantly ($p = 0.01$) downstream from the Panhandle, exhibiting a trend of Mohembo < Sepopa < Etsatsa < Crescent < Guma. Figure 2b shows cyclical trends and differences in salt concentration between the upper and lower Panhandle. Significant variations between low and high floods were observed, with higher conductivities at low floods.

The concentration of dissolved oxygen in the Panhandle ranged from 0.2 to 8.9 mg/l. Dissolved oxygen was significantly higher at Mohembo compared to the other four sites, with the lowest concentrations at Crescent Island. Figure 2c shows consistently lower DO levels at Guma compared to Mohembo during the study period. An ANOVA test showed significant differences among sampling locations and at flood stages, with high DO levels at low floods and low concentration levels at high floods.

Measurements of turbidity showed a range of 0.3–21.7 NTU across sampling sites. Turbidity showed significant differences between sites, with more turbid waters at Mohembo compared to Guma. Significant variation was also observed between low and high floods, with the highest turbidity at low floods. Figure 2d highlights the turbidity variations over time at Mohembo and a different environment at Guma, where turbidity is relatively uniform throughout the study period.

Major cations analysed in the river water were calcium, magnesium, sodium, and potassium, while the anions analysed were bicarbonates, chlorides, and sulphates. Concentrations of cations ranged from undetectable levels to 32.8 mg/l of calcium recorded at Crescent Island, whereas anions ranged from undetectable levels to 130 mg/l of bicarbonate at Sepopa. Of particular interest at Sepopa is another high value of sulphate, at a concentration of 120 mg/l. The Okavango Panhandle waters were found to be of a calcium bicarbonate type, dominated by calcium and bicarbonate ions. A general concentration increase downstream was observed for these major ions (Tab. 1).

Discussion

Water quality in rivers and streams is generally linked with land cover and land use patterns in the catchment (Ngoye & Machiwa, 2004). The most sustainable freshwater sources in the world originate in forest ecosystems (Neary et al., 2009). Forest surfaces act as water filters because they have high organic matter content, which also increases the stability of soil aggregates, reducing soil erosion and moderating sediment and nutrient fluxes (Neary et al., 2009). The water quality of the Okavango delta has been reported to fluctuate spatially and seasonally (Gondwe & Masamba, 2016; West et al., 2015). These variations were said to be influenced by climate and geology as well as the pulsing of the river (Mackay et al., 2011). Nevertheless, clearing of land for human settlements, large-scale agriculture, and increased tourist facilities may all contribute to the deterioration of water quality in the delta.

Discharge

Though not a basic water quality parameter, discharge is reported in this paper because it has been reported to influence the water chemistry of the Okavango delta (Mackay et al., 2011). The highest measured discharge in 2017 was lower than for the other years. The data are not reliable, however, as equipment broke down and there were no measurements of discharge during very high floods that year.

Temperature

The time series plots (Fig. 2a) for water temperature show a fairly stable, seasonal cyclical variation with no apparent trend. These repetitive patterns may form because the riparian vegetation with thick forest canopies shields and protects the waters from heating up too much in summer despite high air temperatures. The stable temperatures may also be a result of the continuous inflow of water from upriver and the effective environmental management practises in protecting the area by minimising land and industrial development around the delta. Temperature influences biochemical reactions and the solubility of gases, especially oxygen in this case. In addition, aquatic organisms have certain a tolerance range for temperature; if it changes quickly by 3°C, it may be lethal to some fish species (Caissie, 2006). The stable temperature among sites and years indicates favourable environmental conditions for aquatic life and sustenance of biodiversity in the Panhandle. A water quality study conducted between 2006 and 2009 (West et al., 2015) reported summer maximum temperatures of 35° C in the Panhandle, similar to maximums obtained for Mohembo and Sepopa in this study (Tab. 1).

pH

The recommended pH range for freshwater ecosystems by US and New Zealand standards (ANZECC, 1992; USEPA, 1992) is 6.5–9.0, and the World Health Organization (WHO, 2006) recommends a range of 6.5–8.5 for drinking water. About 57% of the samples of the Panhandle were within these international water quality standards, and 1.7% of samples were in the range of 5.1 to 5.5, a range where fish and other aquatic organisms will experience very restricted populations and fish eggs and larvae may die (Robertson-Bryan, 2004). The pH of the study sites decreased from Mohembo to Guma, probably as a result of increased concentrations of humic acids from the decomposition of aquatic plants brought in from upstream. During low floods, the higher pH may be attributed to the increased evaporation rate, which results in a concentration of salts in the river water. Wetlands have good buffering capacity, however, and this may explain why the year-to-year variations in pH were not significant. A study carried out in 2000 (Ashton et al., 2003) reported a mean pH of 6.74 in Mohembo (Gondwe & Masamba, 2016), a study conducted between 2008 and 2010 reported a mean of 6.92, and the present study reported a mean pH of 6.6.

Electrical conductivity

Despite an estimated annual input of about 381,000 t of solutes from upstream (McCarthy & Ellery, 1998), electrical conductivity of the upper delta recorded in this study was relatively low (27.3–99.8 µS/cm; Tab. 1) compared to other natural systems on the globe, which may vary between 1 and 1,500 µS/cm (WHO/UNEP, 1989). Research has shown that the bulk of the incoming solutes in the Okavango River are removed from surface waters by density-driven sinking of saline waters, and then stored beneath the delta's islands (McCarthy & Ellery, 1998). EC in the Panhandle increased downstream, with Mohembo having the lowest and Guma the highest (Fig. 2b). This observed salt concentration gradient was also documented in past studies (Ashton et al., 2003; Ellery et al., 2003; Gondwe & Masamba, 2016) and attributed to evapotranspiration leading to reduced water mass and thus an increase in the concentration of salts. Significantly higher EC was observed at low floods as a result of increased evaporation rates and salt enrichment in river waters, whereas at high floods, dilution effects resulted in low EC values.

Dissolved oxygen

Except for the seasonal differences, no changes in DO for the 3-year period of study were noticed. The Environmental Protection Agency (EPA, 1986) recommends a DO range of 5.0–9.5 mg/l for warm-water aquatic species at various life stages. A minimum of 2.4 mg/l DO is required for the survival of aquatic life (Mmualefe & Torto, 2011). In the Panhandle, concentration ranges from 0.2 mg/l to 8.9 mg/l were recorded. During high floods, minimum concentrations recorded at each sampling site were below 1 mg/l, but the annual mean values were above 2.6 mg/l (Tab. 1). Strong seasonal fluctuations take place, however, and of major concern is the depletion of dissolved oxygen occurring during high floods. This can be attributed to high biological oxygen demand associated with fine organic material that is mobilised by the flood waters. Fish kills have been reported by communities of the Okavango Panhandle during high floods, and the low concentration of oxygen may well be the reason for the fish kills. The lowest concentration of DO was recorded at Crescent Island, which may be due to point pollution sources from a nearby safari camp, demonstrating potential negative effects of some tourism activities on river water quality.

Turbidity

Turbidity in the Panhandle decreases downstream (Tab. 1). This decrease may be due to the filtration processes and the sedimentation of the suspended matter, with increasing distance as the river meanders downstream. Figure 2d shows the variation of turbidity at Mohembo and Guma, where Guma is much lower compared to Mohembo. Seasonally, turbidity was higher during low floods across all the study sites except Guma lagoon.

Major ions

The Okavango Panhandle is a freshwater system with low dissolved salts, as shown by the low conductivity values (< 100 µS/cm) obtained in this study and in previous studies (Mackay et al., 2011; Mmualefe & Torto, 2011). Chemical weathering and the resulting physical erosion of the parent material soils contribute significantly to the chemical composition of river water (Huang et al., 2009). These processes are accentuated by increased temperature and land cover clearing. The higher concentrations of calcium and bicarbonate in the Panhandle may be attributed to weathering of carbonate rocks in the headwaters. Concentrations of all major ions were very similar (within the same order of magnitude) to values obtained by Ashton et al. (2003) and Mackay et al. (2011). This similarity suggests that the river water has not been affected by upstream activities.

Conclusion

The study demonstrates that the general water quality of the Okavango Panhandle with respect to the parameters measured (temperature, pH, conductivity, dissolved oxygen, turbidity) was relatively good; most samples were within international guidelines for freshwater ecosystems. Cyclical seasonal variations of water quality parameters occurred, influenced by changes in temperature and flood levels, but no significant year-to-year variations were observed. Spatially, there were no significant differences in temperature, but other parameters showed significant variability that may be attributed to geology, soils, and land cover. There were no significant temporal (year-to-year) variations of water quality parameters, and this may reflect the effectiveness of the Okavango water resources management. However, human-related pressures are being experienced in the Namibian Kavango area, where population growth has led to land clearing and economic development has led to large-scale irrigation schemes and intensification of cattle production. These activities are likely to deposit residual fertilisers, pesticides, and nutrients in the Okavango River, deteriorating the water quality. Continuous water quality monitoring of the entire Okavango River system is critical for sustainability of the resource.

Acknowledgements

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References

Australian and New Zealand Environment and Conservation Council (ANZECC) (2000) *Australian and New Zealand guidelines for freshwater and marine water quality*. Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

Ashton, P.J. et al. (2003) A rapid biological assessment of the aquatic ecosystems of the Okavango Delta, Botswana: high water survey. *RAP Bulletin of Biological Assessment* (ed. by L.E. Alonso & L.-A. Nordin), pp. 38–53. Conservation International, Washington, DC.

Caissie, D. (2006) The thermal regime of rivers: a review. *Freshwater Biology*, **51**, 1389–1406.

Carr, G.M. & Neary, J.P. (2008) *Water quality for ecosystem and human health.* UNEP/Earthprint, Ontario.

Ellery, W.M., McCarthy, T.S. & Smith, N.D. (2003) Vegetation, hydrology and sedimentation patterns on the major distributary system of the Okavango Fan, Botswana. *Wetlands*, **2003**, 357–375.

Gondwe, M.J. & Masamba, W.R.L. (2016) Variation of physico chemical parameters along a river trancsect through the Okavango Delta, Botswana. *African Journal of Aquaitc Science*, **41**, 205–215.

Gumbricht, T., Wolski, P., Frost, P. & McCarthy, T.S. (2004) Forecasting the spatial extent of the annual flood in the Okavango Delta, Botswana. *Journal of Hydrology*, **290**, 178–191.

Huang, X., Sillanpaa, M., Gjessing, E.T. & Vogt, R.D. (2009) Water quality in the Tibetan Plateau: major ions and trace elements in the headwaters of four major Asian rivers. *Science of the Total Environment*, **407**, 6242–6254.

Mackay, A.W. et al. (2011) Spatial and seasonal variability in surface water chemistry in the Okavango Delta, Botswana: a multivariate approach. *Wetlands*, **31**, 815–829.

Masamba, W.R. & Mazvimavi, D. (2008) Impact on water quality of land uses along Thamalakane-Boteti-River. *Physics and Chemistry of the Earth, Parts A/B/C*, **33**, 687–694.

Masamba, W.R. & Muzila, A. (2005) Spatial and seasonal variation of major cations and selected trace metals in the Okavango-Maunachiri-Khwai channels of the Okavango Delta. *Botswana Notes and Records*, **37**, 218–226.

McCarthy, T.S. & Ellery, W.N. (1998) The Okavango Delta. *Transactions of the Royal Society of South Africa*, **53**, 157–182.

Mmualefe, L.C. & Torto, N. (2011) Water quality in the Okavango Delta. *Water SA*, **37(3)**, 411–418.

Neary, D.G., Ice, G.G. & Jackson, R. (2009) Linkages between forest soils and water quality and quantity. *Forest Ecology and Management*, **258**, 2269–2281.

Ngoye, E. & Machiwa, J.F. (2004) The influence of land-use patterns in the Ruvu river watershed on water quality in the river system. *Physics and Chemistry of the Earth*, **29**, 1161–1166.

Propper, M., et al. (2015) *The future Okavango - findings, scenarios and recommendations for action. Research project final synthesis report, 2010–2015.* University of Hamburg, Biocentre Klein Flottbek, Hamburg.

Rice, E.W., Baird, R.B., Eaton, A.D. & Clesceri, L.S. (2012) *Standard methods for the examination of water and wastewater, 22nd edition.* American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC..

Sawula, G. & Martins, E. (1991) Major ion chemistry of the lower Boro River, Okavango Delta, Botswana. *Freshwater Biology*, **26**, 481–493.

Tubatsi, G., Bonyongo, M.C. & Gondwe, M. (2014) Water quality in the Boro-Thamalakane-Boteti river system, northern Botswana. *African Journal of Aquatic Science*, 39, 351–360.

Vushe, A., Haimene, E.P. & Mashauri, D. (2014) Namibian land use changes and nutrient water quality of the Okavango River. *Journal of Agriculture and Environmental Sciences* (American Research Institute for Policy Development), 3, 219–239.

West, D.T., van As, J.G. & van As, L.L. (2015) Surface water quality in the Okavango Delta panhandle, Botswana. *African Journal of Aquatic Science*, 40, 359–372.

World Health Organization (2006) *Guidelines for drinking water quality.* WHO, Geneva.

References [CrossRef]

Australian and New Zealand Environment and Conservation Council (ANZECC) (2000) *Australian and New Zealand guidelines for freshwater and marine water quality*. Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

Ashton, P.J. et al. (2003) A rapid biological assessment of the aquatic ecosystems of the Okavango Delta, Botswana: high water survey. *RAP Bulletin of Biological Assessment* (ed. by L.E. Alonso & L.-A. Nordin), pp. 38–53. Conservation International, Washington, DC.

Caissie, D. (2006) The thermal regime of rivers: a review. *Freshwater Biology*, **51**, 1389–1406. CrossRef

Carr, G.M. & Neary, J.P. (2008) *Water quality for ecosystem and human health.* UNEP/Earthprint, Ontario.

Ellery, W.M., McCarthy, T.S. & Smith, N.D. (2003) Vegetation, hydrology and sedimentation patterns on the major distributary system of the Okavango Fan, Botswana. *Wetlands*, **2003**, 357–375. CrossRef

Gondwe, M.J. & Masamba, W.R.L. (2016) Variation of physico chemical parameters along a river trancsect through the Okavango Delta, Botswana. *African Journal of Aquaitc Science*, **41**, 205–215. CrossRef

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Huang, X., Sillanpaa, M., Gjessing, E.T. & Vogt, R.D. (2009) Water quality in the Tibetan Plateau: major ions and trace elements in the headwaters of four major Asian rivers. *Science of the Total Environment*, **407**, 6242–6254. CrossRef

Mackay, A.W. et al. (2011) Spatial and seasonal variability in surface water chemistry in the Okavango Delta, Botswana: a multivariate approach. *Wetlands*, **31**, 815–829. CrossRef

Masamba, W.R. & Mazvimavi, D. (2008) Impact on water quality of land uses along Thamalakane-Boteti-River. *Physics and Chemistry of the Earth, Parts A/B/C*, **33**, 687–694. CrossRef

Masamba, W.R. & Muzila, A. (2005) Spatial and seasonal variation of major cations and selected trace metals in the Okavango-Maunachiri-Khwai channels of the Okavango Delta. *Botswana Notes and Records*, **37**, 218–226. CrossRef

McCarthy, T.S. & Ellery, W.N. (1998) The Okavango Delta. *Transactions of the Royal Society of South Africa*, **53**, 157–182.

Mmualefe, L.C. & Torto, N. (2011) Water quality in the Okavango Delta. *Water SA*, **37(3)**, 411–418. CrossRef

Neary, D.G., Ice, G.G. & Jackson, R. (2009) Linkages between forest soils and water quality and quantity. *Forest Ecology and Management*, **258**, 2269–2281. CrossRef

Ngoye, E. & Machiwa, J.F. (2004) The influence of land-use patterns in the Ruvu river watershed on water quality in the river system. *Physics and Chemistry of the Earth*, **29**, 1161–1166. CrossRef

Propper, M., et al. (2015) *The future Okavango - findings, scenarios and recommendations for action. Research project final synthesis report, 2010–2015.* University of Hamburg, Biocentre Klein Flottbek, Hamburg.

Rice, E.W., Baird, R.B., Eaton, A.D. & Clesceri, L.S. (2012) *Standard methods for the examination of water and wastewater, 22nd edition.* American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC..

Sawula, G. & Martins, E. (1991) Major ion chemistry of the lower Boro River, Okavango Delta, Botswana. *Freshwater Biology*, **26**, 481–493. CrossRef

Tubatsi, G., Bonyongo, M.C. & Gondwe, M. (2014) Water quality in the Boro-Thamalakane-Boteti river system, northern Botswana. *African Journal of Aquatic Science*, **39**, 351–360. CrossRef

Vushe, A., Haimene, E.P. & Mashauri, D. (2014) Namibian land use changes and nutrient water quality of the Okavango River. *Journal of Agriculture and Environmental Sciences* (American Research Institute for Policy Development), **3**, 219–239.

West, D.T., van As, J.G. & van As, L.L. (2015) Surface water quality in the Okavango Delta panhandle, Botswana. *African Journal of Aquatic Science*, **40**, 359–372. CrossRef

World Health Organization (2006) *Guidelines for drinking water quality.* WHO, Geneva.

The SASSCAL Data and Information Portal

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The SASSCAL Data and Information Portal is an open online data and information portal that can be accessed freely using any web browser at http://data.sasscal.org (Fig. 1).

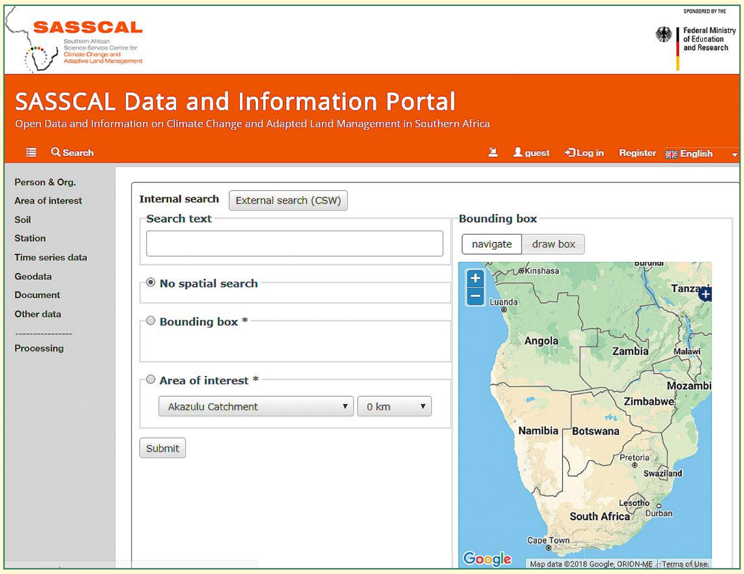

Figure 1: Landing page of SASSCAL Data and Information Portal

As a central data and information hub, the SASSCAL Data and Information Portal allows for the management, analysis, visualisation, linkage, and presentation of various types of resources, including time series data, geospatial data, documents, and others (Fig. 2). Its powerful search functionality is supported by comprehensive metadata records for all resources that the system makes available. The system is fully interoperable, highly user-friendly, and receives high-level acceptance among users from a wide user community, demonstrated by an average of 50,000 page impressions per month.

At the end of 2017, the SASSCAL Data and Information Portal contained data from 640 environmental measurement stations, including more than 700 hydro-climatic time series data records and more than 250 geospatial data sets from more than 70 regional and international organisations, as well as numerous documents. Data are added continuously. Resources can be searched using keywords, temporal or spatial extent, and by means of predefined areas of interest, such as district boundaries or study sites.

Implemented and operated by the SASSCAL Open Access Data Centre (OADC), the SASSCAL Data and Information Portal ensures that the research deliverables resulting from the SASSCAL 1.0 Research Portfolio are hosted and made available according to stakeholder demands. The portal offers a fine-grained user permission control approach which allows the data owner to upload and update data but also permits setting up access permissions.

Notably, the resources hosted by the SASSCAL Data and Information Portal are not limited to the SASSCAL research outputs, but also extend to publicly accessible data from other sources relevant to SASSCAL researchers and stakeholders, including the research community, decision makers and the public.

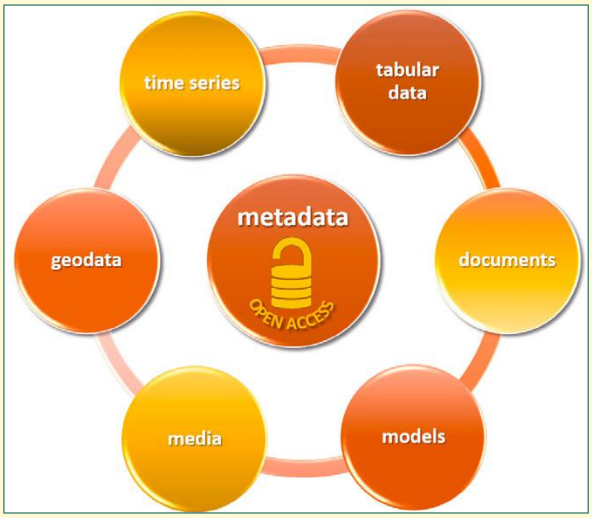

Figure 2: Supported data types of the SASSCAL Data and Information Portal

System architecture and functionalities of the SASSCAL Data and Information Portal

The SASSCAL Data and Information Portal is based exclusively on open source solutions, while ensuring data interoperability and allowing extensibility. The system is based on a three-tier architecture with user frontends and server functionality for database operations (Fig. 3). All data are processed on the server, putting less strain on hardware capacity at the end user's side.

Following a fully open-source approach, the system builds on PostgreSQL/PostGIS databases for data management, an Apache HTTP Server for web services, and a CSW server for metadata representation, and implements the Bootstrap web framework with different JavaScript libraries to create a user-friendly and intuitive graphical user interface. The metadata model is based on ISO standards (e.g., ISO, 2005) and further adheres to specifications of gazetted metadata standards in the SASSCAL countries. A full description of the technical details of the SASSCAL Data and Information Portal can be found in Zander and Kralisch (2016).

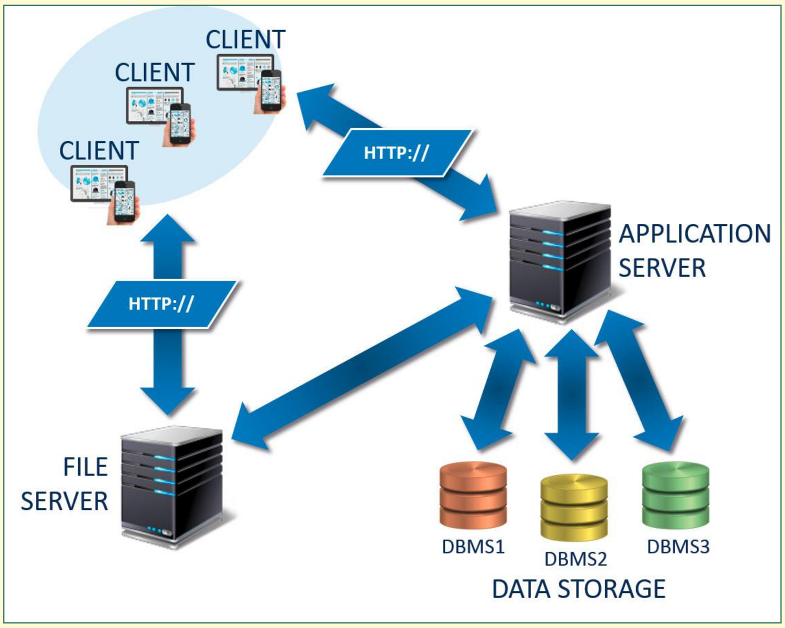

Figure 3: SASSCAL Data and Information Portal architecture

In its current version, the SASSCAL Data and Information Portal offers a wide range of functionalities. Advanced gap analysis for time series data, visualisation, and manual and automated import/export tools for various data types have been implemented, as have sophisticated web mapping functions for geospatial data exploration. Geospatial data and metadata are provided through standardised web services.

Outlook for the SASSCAL Data and Information Portal

The SASSCAL Data and Information Portal architecture serves the SASSCAL objective in developing and operating a regional resource and data hub for southern Africa. Its current functionalities already ensure that it can host data and information from any relevant research project. To allow for the consideration of new user demands, the data portal will be continuously enhanced in the future. For example, it will cater to the integration of additional data processing and analysis tools; advanced hydrological, climate, and other environmental models; and offer a link to other SASSCAL data products, such as SASSCAL WeatherNet (Muche et al., 2018; www.sasscalweathernet.org) and the SASSCAL observations net (Hillmann et al., 2018; www.sasscalobservationnet.org). The integration of advanced filter and search tools, documentation, and online help functions will ensure a seamless and intuitive user experience.

The SASSCAL Data and Information Portal aims at providing open online data and information resources, but at the same time intends to protect the intellectual property rights of the scientific and research community. Providing user functions for data access, but also for uploading new data, it serves as a flexible one-stop solution for data management, data exchange, and dissemination of research results.

References

Hillmann, T., Muche, G., Josenhans, K. & Jürgens, N. (2018) Online presentation of the SASSCAL ObservationNet. This volume.

ISO (2005) International Standard ISO 19115 Geographic Information—Metadata—Part 1: Fundamentals (ISO 19115-1:2005); ISO, Geneva, Switzerland.

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: present state, challenges, and achievements of the regional climatic observation network and database. This volume.

Zander, F. & Kralisch, S. (2016) River Basin Information System: Open environmental data management for research and decision making. *ISPRS International Journal of Geo-Information*, **5**, 123.

Water resources

Semi-arid catchments under change: Adapted hydrological models to simulate the influence of climate change and human activities on rainfall-runoff processes in southern Africa

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Abstract: A comprehensive river basin assessment is key to integrated land and water resources management (ILWRM), which is based on an integrated system analysis to identify interacting hydrological processes that are driven by landscape features and socioeconomic development. Software toolsets like RBIS (River Basin Information System), GRASS-HRU, and the hydrological modelling system JAMS/J2000 were used and further developed for basin assessments and modelling of hydrological process dynamics and other environmental processes in selected catchments in southern Africa. These are the Gaborone Dam catchment (Botswana, South Africa), the Verlorenvlei catchment (South Africa), and the Luanginga catchment (Angola, Zambia). All of these catchments respond very sensitively to changes in climate and land management, revealing additional issues like a strong decline of inflow (Gaborone Dam) or a decline of usable groundwater resources (Verlorenvlei). Further, extensive wetland areas in the Upper Zambezi (Luanginga) respond strongly to changes in hydro-climatic conditions and land management. In this study, newly developed and improved simulation components for representing processes with a strong local impact on the hydrological conditions such as floodplain inundation, irrigation, small farm dams, and contour bank farming were used to more precisely simulate the hydrology of the respective basins. After successful model validation and an improved understanding of catchment dynamics, the models were used as a platform for different land or climate change analysis. Taking the RCP 8.5 scenario based on EC-Earth and ECHAM, downscaled by REMO, into account, the Luanginga catchment showed a strong decrease in runoff generation, inundation extent, and groundwater recharge. For the Kruismannsrivier, a sub-catchment of the Verlorenvlei, the relation between contour farming and related effects on surface/subsurface runoff processes and related parameters were revealed through modelling. These findings could also be projected to the Gaborone Dam catchment, in which the influence of small farm dams spread over the catchment could be shown by modelling.

Resumo: Uma avaliação abrangente da bacia hidrográfica é essencial para a gestão integrada dos recursos terrestres e hídricos (ILWRM), a qual é baseada numa análise integrada do sistema para identificar processos hidrológicos em interacção que são impulsionados pelas características da paisagem e o desenvolvimento socioeconómico. Ferramentas de software, tais como RBIS (River Basin Information System), GRASS-HRU e o sistema de modelação hidrológica JAMS/J2000, foram utilizadas e desenvolvidas para avaliações de bacias e modelação de dinâmicas de processos hidrológicos e outros ambientais em bacias selecionadas na África Austral. Estas são a bacia de Gaborone Dam (Botswana, África do Sul), bacia de Verlorenvlei (África do Sul) e bacia de Luanginga (Angola, Zâmbia). Todas estas bacias hidrográficas são muito sensíveis a alterações no clima e na gestão das terras, revelando problemas adicionais como um forte declínio no influxo (Gabarone

Dam) ou um declínio nos recursos hídricos subterrâneos utilizáveis (Verlorenvlei). Além disso, extensas áreas de zonas húmidas no Zambezi Superior (Luanginga) respondem fortemente a alterações nas condições hidro-climáticas e na gestão das terras. Neste estudo, foram utilizados componentes de simulação recentemente desenvolvidos e melhorados para representar processos com um forte impacto local nas condições hidrológicas, tais como inundação de várzeas, irrigação, pequenas barragens agrícolas e agricultura de contorno, para simular com maior precisão a hidrologia das respectivas bacias. Após a validação bem-sucedida do modelo e uma melhor compreensão das dinâmicas das bacias, os modelos foram usados como uma plataforma para diferentes análises da terra e das alterações climáticas. Tendo em conta o cenário do RCP 8.5, baseado em EC-EARTH e ECHAM, downscaled pelo REMO, a bacia de Luanginga mostrou uma forte diminuição na produção de escorrência superficial, extensão de inundação e recarga de águas subterrâneas. Para o Kruismannsrivier, uma sub-bacia do Verlorenvlei, a relação entre a agricultura de contorno e os impactos relacionados com os processos de escorrência superficial/subterrânea (e parâmetros relacionados) foram revelados pela modelação. Estas descobertas podiam ser também projectadas para a bacia de Gaborone Dam, na qual a influência de pequenas barragens agrícolas espalhadas pela bacia podia ser demonstrada através da modelação.

Introduction

Background

Sustainable water management in semi-arid areas is a challenge from various perspectives. Given the projected changes in climate as well as ongoing population growth and associated demands for food and energy production that result in land management changes, a key challenge in the sub-Saharan countries is to secure water at sufficient quality and quantity for both the stability of ecosystems, with their requisite functions and services, and for human use. Changing conditions will severely influence the highly variable hydrological pattern in southern African catchments, including, for example, increasing extremes, changing groundwater recharge patterns, or increasing water extraction and pollution. These effects, in turn, will create even more pressure on ecosystems, existing and future land management, socio-economic development, and biodiversity. Consequently, southern Africa is suspected to be strongly affected by global climate change and shows a high climate vulnerability and risk (Miola & Simonet, 2014), with climate extremes presumed to intensify in frequency and magnitude (SREX, 2012). Due to recent droughts resulting from an El Niño event, water managers are challenged with questions such as: Can we cope with the demands on water (e.g., water shortages in Gaborone or Windhoek; Allgemeine Zeitung, 2016; Mmegi, 2016) or can we provide enough energy to further develop southern African economies (e.g., lack of production at Lake Kariba; IGC, 2016; New York Times, 2016)? To manage such interrelated phenomena in data-scarce regions like southern Africa, innovative modelling techniques can be successfully applied.

Precipitation in the semi-arid regions of southern Africa is highly variable; rainfall is of relatively short duration, highly localised, and often occurs with different intensities (Hughes, 2007). Various studies over the previous decades have shown that extreme rainfall events make up a significant share of the total annual precipitation (e.g., Mason et al., 1997; Güntner, 2002; van Wilgen et al., 2016). Highly variable precipitation events also cause a strong variability in the discharge behaviour of rivers in southern Africa (e.g., Mazvimavi & Wolski, 2006; Steudel et al., 2013a; Kusangaya et al., 2014). Partly due to this high variability, the runoff at the west coast of Western Cape province is most sensitive to climate change all over South Africa (Schulze, 2000). In addition, low latitudes and high radiation lead to high annual mean temperatures and therefore to a high potential evapotranspiration (e.g., Alexander, 1985; Steudel et al., 2013a, 2013b; Engelbrecht et al., 2015) which may result in severe droughts in years with only small amounts of rainfall. In areas affected by unsustainable management practices, climatic and hydrological extremes increase already existing trends towards desertification, erosion, and a related loss of biodiversity, water, and food insecurity (Meigh, 1995; Hughes, 2007; Wheater, 2008). To represent the complex interacting natural and human-induced drivers in hydrological models in an appropriate, process-oriented way, advanced and adaptive modelling tools and methods are needed (Parida et al., 2006; Wheater, 2008).

Objectives

The aforementioned challenges are predominant in the three pilot catchments investigated in this study, all located in semi-arid southern Africa (Fig. 1). The overall aim of this work, which was embedded in SASSCAL Task 18, was the development of eco-hydrological computer models that are tailored to the specific conditions in the selected river basins, both in terms of dominant processes and data availability. Further, these models were required to represent eco-hydrological and anthropogenic processes using physically based, conceptual approaches in order to make them applicable for assessing the impacts of land management and climate change, and thus to provide a basis for informed water resources management in the selected pilot catchments.

To achieve these objectives, rainfall-runoff dynamics of the often data-poor areas were reproduced by utilising the integrated, process-based, and spatially distributed modelling system JAMS/J2000 (Kralisch & Krause, 2006). The first objective was to simulate the undisturbed

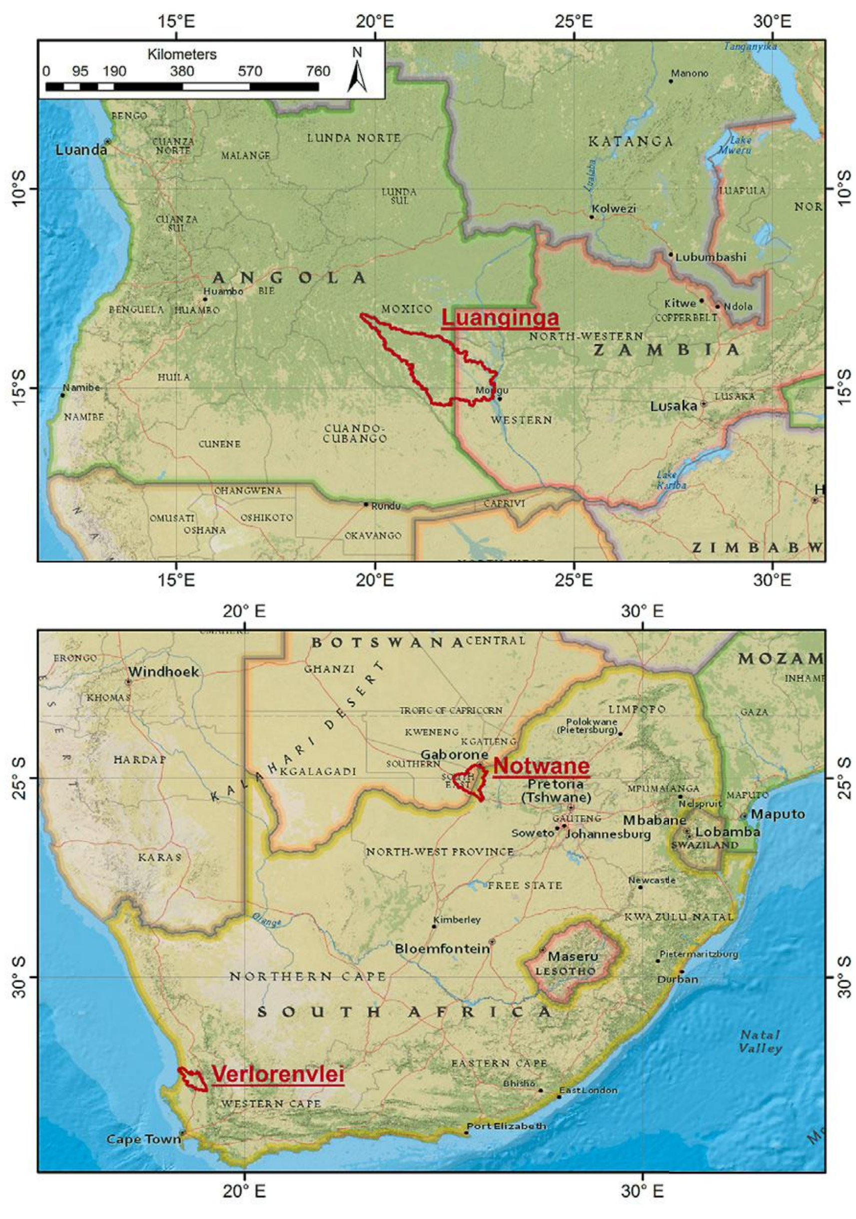

Figure 1: Location of the pilot catchments (red).

natural conditions of the hydrological systems in the three pilot catchments. The second objective focused on the representation of major anthropogenic factors apparently influencing the hydrological conditions within two of the pilot catchments, namely the Gaborone Dam and Verlorenvlei catchments. By implementing additional simulation routines, the models were adapted to more precisely reflect specific local conditions in both pilot catchments and to improve model performance (e.g., advanced routing techniques and modules simulating the influence of small farm dams, irrigation, and contour farming). The third objective was to assess the effects of climate change on the hydrological process dynamics in the other pilot catchment, the Luanginga catchment. In this catchment, the focus was on developing a model extension capable of simulating the annual flooding condition and therefore to provide a more realistic simulation of hydrological components like runoff generation, evapotranspiration, and soil moisture. Using this model, the climate change impact has been analysed up to the year 2100. Special attention was paid to investigating how the newly developed flood extension responds to climate change and how this impacts flood dynamics and extent. However, the developed model also provides the basis for follow-up assessments with more comprehensive climate projection data sets.

Study Areas

Verlorenvlei

The Verlorenvlei catchment (~1 820 km²; Fig. 1) drains into an estuarine lake, a RAMSAR-listed wetland on the west coast of South Africa within the Sandveld area; the intermittent connection between fresh and salt water is connected to a high biodiversity profile. The Sandveld region has a Mediterranean climate, characterised by cool, rainy winters and hot, dry summers (Franke et al., 2014). Precipitation is in the form of coastal fog and low and variable rainfall (Conrad & Munch, 2006). Furthermore, the area experiences wide ranging inter-annual climatic variability. The highest annual rainfall was recorded at in the upper catchment with 589 mm in 2001, whereas the coastal area received the lowest rainfall, 115 mm in 2002. Potential evapotranspiration (PET) ranges from 1 200 mm per year to 1 600 mm per year, mostly exceeding rainfall rates; even the lowest PET is in excess of the highest rainfall (Conrad & Munch, 2006).

The catchment is an important agricultural area, providing 15% of the South African potato crop (Potatoes South Africa, 2015). Some tea and fruits are also grown, but play only a minor role for the majority of the farmers (Archer et al., 2009). The catchment is exposed to several challenges, such as climate change and decreasing groundwater levels combined with an increasing irrigation agriculture, representing a hydrologically vulnerable area within the Sandveld (Conrad & Munch, 2006). The water users in Verlorenvlei area are highly dependent on groundwater, as surface water resources are scarce. Most cities and irrigation systems in the region are supplied with groundwater. The only dams used for irrigation can be found in the more mountainous headwaters. A single subcatchment providing good quality water, the Krom-Antonies, is the system's main provider of fresh water—almost all other sub-catchments are facing salinity difficulties (Conrad & Munch, 2006). Thus, the catchment is considered as a good example of South Africa's coastal areas, where water scarcity may be a limiting factor for economic development. The correct evaluation of water resources, as well as their

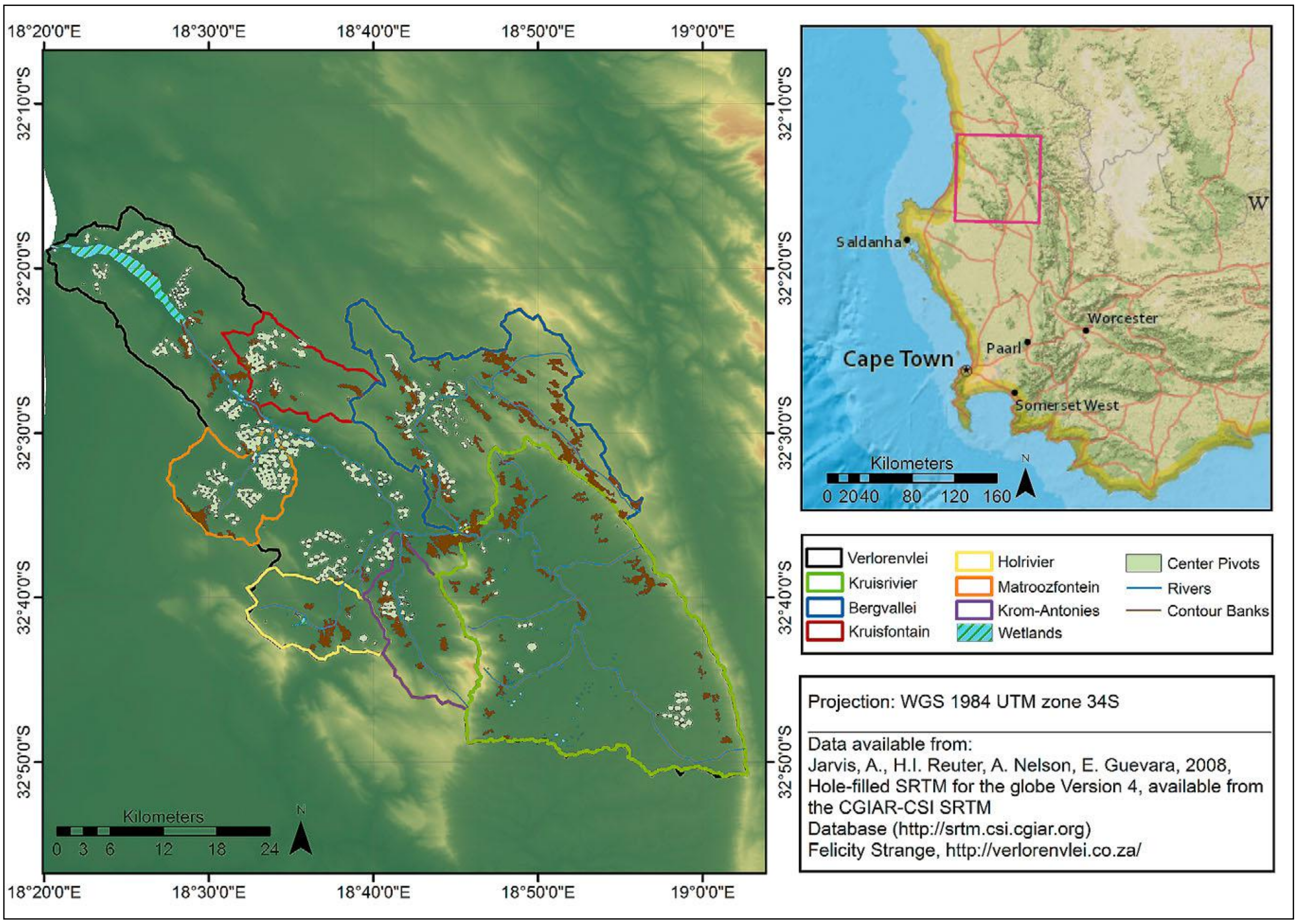

Figure 2: Sub-catchments of the Verlorenvlei and location of centre pivots and contour banks

quality and monitoring, are crucial for the sustainable use of water in this coastal area, where agricultural interests must be considered as well (Nel, 2004).

Two agricultural implementations that will be further discussed in this paper, centre pivot irrigation and contour bank farming (Fig. 2), are apparent in the catchment. Contour farming is a common practice for water and soil conservation in the Western Cape Province (Wakindiki et al., 2007). Contour banks are constructed perpendicular to cultivated slopes, as well as at specific intervals downslope. Their main purpose is to reduce slope lengths and water flow velocity and to store and prolong surface runoff. The impact of contour bank farming on flood reduction and sediment dynamics has been studied in various semi-arid basins (Kingumbi et al., 2004; Nasri, 2007; Baccari et al., 2008; Lesschen et al., 2009; Ouessar et al., 2009; Steudel et al., 2015). In centre pivots, sprinklers are attached below lateral pipes, which are used as a water supply. They represent a typical pattern of sprinkler irrigation (Omary et al., 1997; Foley, 2008). In the Sandveld area, the volume of water applied through irrigation exceeds the natural rainfall by a factor of between 3 in winter and 5 in summer months (Knight et al., 2007).

As no measured runoff series was available for the whole Verlorenvlei catchment, results presented within this study are for the sub-catchment of Kruisriver at station Tweekuilen (G3H001). This station provided a sufficient time series from 1970–2009 with only 3.2% missing data. Both mentioned agricultural implementations are apparent in this sub-catchment.

Gaborone Dam

The Gaborone Dam catchment (4 500 km²), which is part of the Notwane River Basin (FAO, 2004), is located in the southeastern part of Botswana and shares a border with South Africa. The dam itself functions as the main water source for Gaborone City and the surrounding settlements (Meigh, 1995; DWA, 2014a). The Notwane River has its source in the Kalahari sandveldt flowing to the northeast until reaching the Limpopo River. About one-third of Botswana's population lives in the Notwane Basin, which includes large developed cities such as Gaborone, Molepolole, Mochudi, Kanye, Lobatse, and Jwaneng. According to Köppen-Geiger classification, the catchment matches the requirements of BSh (hot, arid steppe) (Peel et al., 2007) with a mean annual temperature of 20.3°C and a precipitation of 450–500 mm/a (Meigh, 1995; Peel et al., 2007). The climate is characterised by a rainy season from November to March and a dry season from April to October. Due to low humidity conditions, a mean PET of about 1 500 mm was estimated by Adams et al. (1999), and PET amounts can be up to four times higher than rainfall (FAO, 2004). All the rivers in the Gaborone Dam catchment are ephemeral. The Gaborone Dam was established in 1963 and was subsequently raised by 25 metres from 1984–1986. This increased its potential capacity from

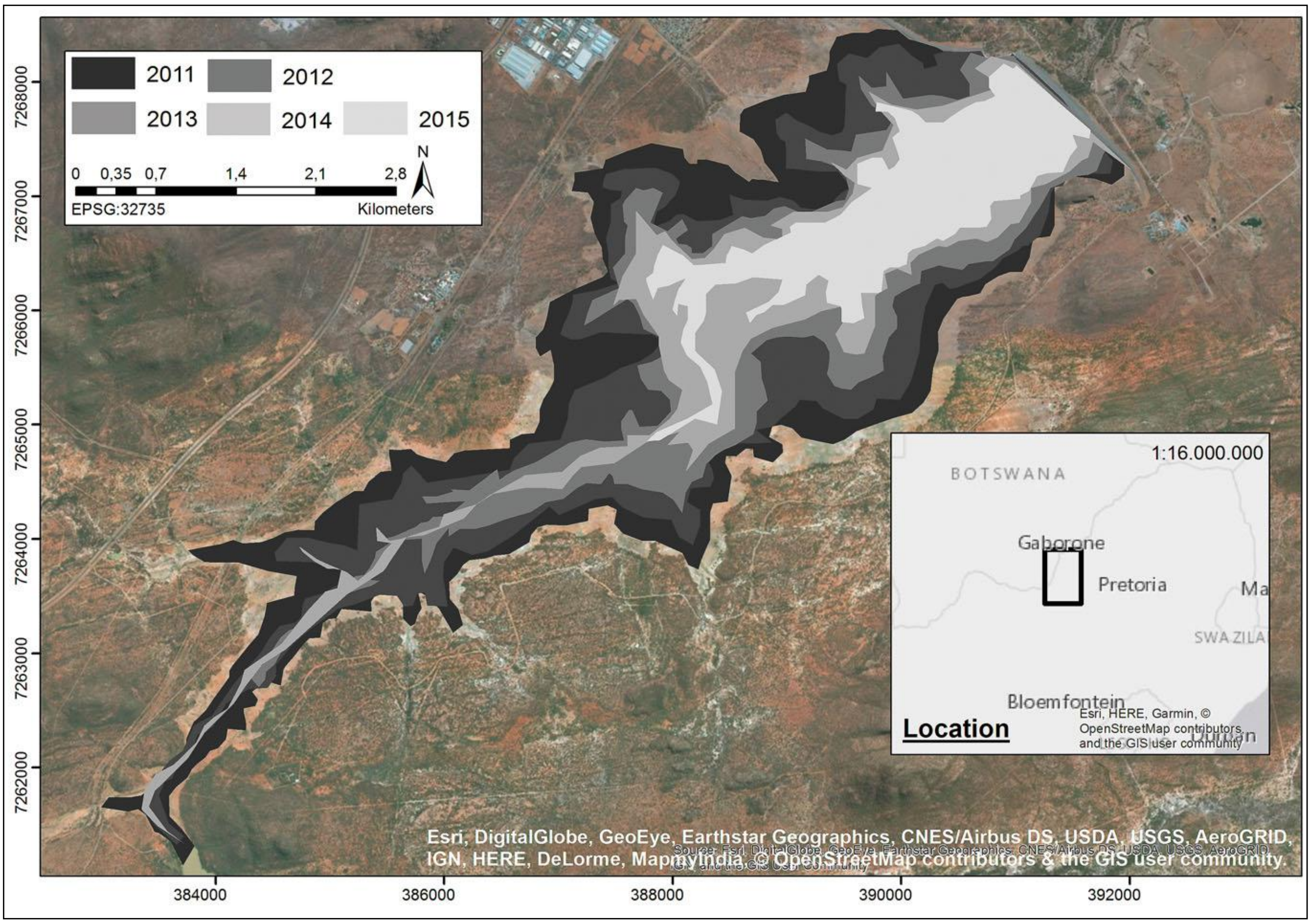

Figure 3: Visualisation of the shrinking size of the Gaborone Dam, Gaborone, Botswana (2011–2015), perimeters derived by digitisation using Landsat 7 and 8 cloud-free scenes at the end of the rainy season (March–May); lines from outside to inside show 2011 to 2015.

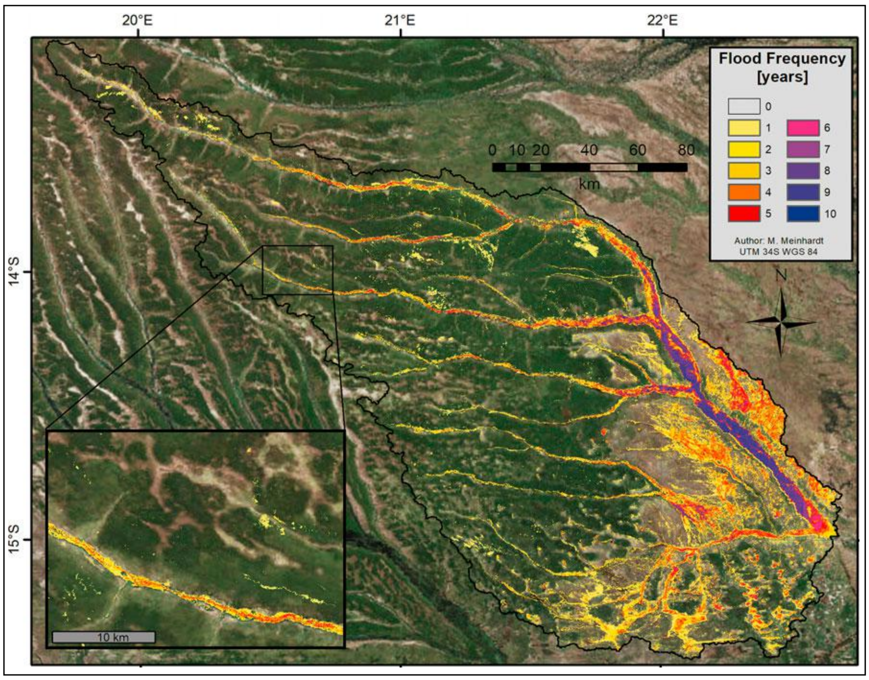

Figure 4: Flood frequency in the Luanginga catchment derived from Landsat/DFI peak flood images based on a time series of 10 years.

23 to 141.1 million cubic meters (Knight, 1990; WUC, 2014). Since 2002, there has been a steady decrease in the volume of the Gaborone Dam (Fig. 3), reaching the lowest record in history of 1% at the end of 2015 (WUC, 2014), leading to failures of water supply (Plessis & Rowntree, 2003).

Luanginga

Wetlands like the Verlorenvlei are especially sensitive to hydrological regime changes (Mitsch & Gosselink, 2000). The third catchment studied here was the Luaginga. It is a tributary of the Upper Zambezi River and covers an area of ~33 000 km², ranging from the Angolan highlands to the Barotse floodplain of the Zambezi River. The catchment is characterised by an annual flow regime and extensive wetland areas upstream of the gauge outlet at Kalabo, the central business district of the area. Due to the annual flood (Fig. 4), which peaks in April, the floodplain consists of exceptionally fertile soils with high agricultural productivity and is also known for its rich cultural heritage. These factors combine to make the area within the watershed particularly sensitive to changes in hydrological conditions because humans, flora, and fauna are adapted to life in this special ecosystem.

To model future changes caused by climate change until the end of this century, two different climate models and two sce-

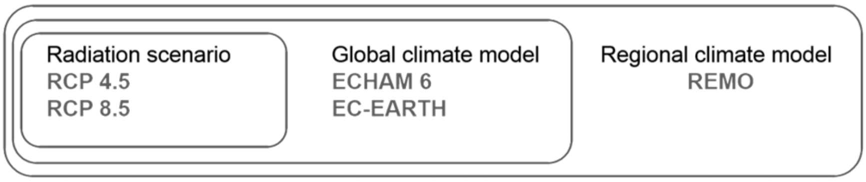

Figure 5: Structure of the applied climate scenarios.

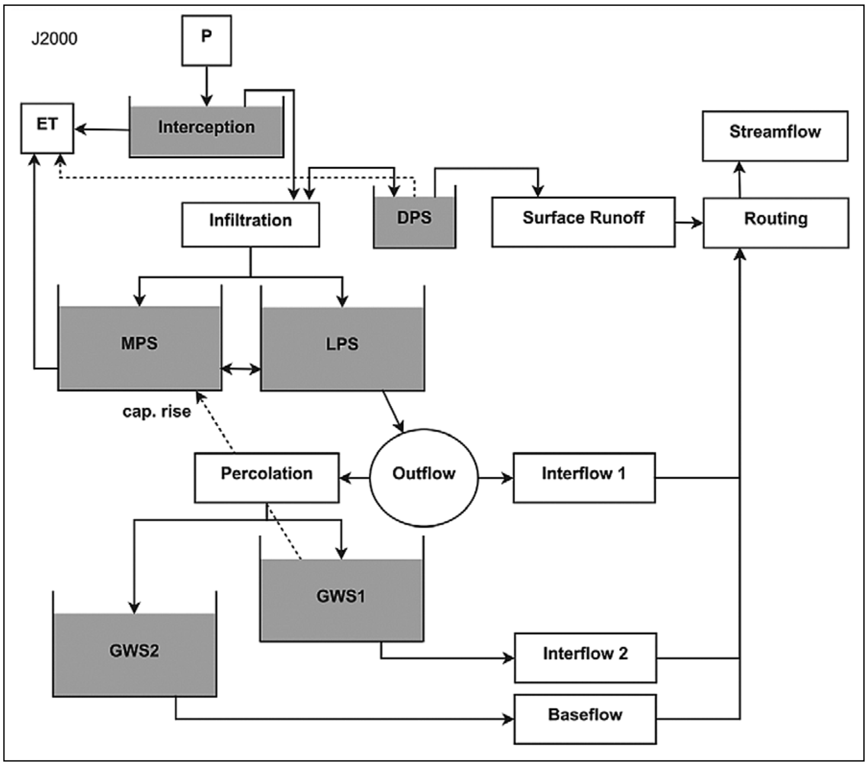

Figure 6: Graphical representation of the J2000 model structure (Knoche et al., 2014). *Abbreviations: DPS – depression storage; MPS – mid-size pore storage; LPS – large pore storage; GWS – groundwater storage.*

narios each were used to run the JAMS/J2000 model in the Luanginga catchment. As shown in Figure 5, they are all based on the regional climate model REMO, which has a high spatial resolution of 0.22 degree (25 km) and is forced either by EHAM or EC-Earth (0.44 degree) using the RCP 4.5 and 8.5 scenarios. The added value of this downscaling performed by the REMO model in comparison to the original ECHAM and EC-Earth data is discussed in Fotso-Nguemo (2017a, 2017b) and mainly based on its higher spatial resolution, which plays a significant role when considering the topography of the catchment, stretching from the Angolan Bié Plateau towards the Zambezi floodplains. Hänsler et al. (2011) showed that in southern Africa, the data (scaled down dynamically with REMO) corresponds to the spatial and temporal patterns of observation, and the seasonal precipitation characteristics are better reproduced by this downscaling compared to the original ECHAM and EC-Earth data with the coarse 0.44 degree resolution. Further, a so-called "scaling" or "simple multiplicative" bias correction (Fowler & Kilsby, 2007; Gudmundsson et al., 2012) based on measured long-term monthly precipitation means was applied to the REMO data as a spatially distributed correction factor in the JAMS/J2000 model, where it is interpolated between the stations and multiplied with the interpolated precipitation for each spatial model entity (Meinhardt, 2017).

The adaptive hydrological modelling system JAMS/J2000

In this section, the main concept of the hydrological model will be described. A detailed explanation of the developed model extensions will be given in the following section.

The process-oriented modelling system JAMS/J2000 was used to address the hydrological dynamics within the pilot catchments. The model consists of encapsulated modules, each of which represents a different hydrological process and runs for different temporal resolutions (Krause, 2001, 2002; Kralisch & Krause, 2006). Following a spatially distributed approach, the model utilises the Hydrological Response Units concept (HRU) (Flügel, 1995; Krause, 2001; Nepal, 2002; Watson et al., 2018) to represent spatial input data. The HRUs were delineated by overlaying information about soil, geology, and relief parameters according to Wolf et al. (2009). Accordingly, J2000 is a spatially fully distributed hydrological model (Krause, 2002) using a routing topology to distribute lateral and surface water budgets between spatial model units (HRUs) along the topographical gradient. Its process-based soil water balance module functions as the central 'regulation and distribution system' (Krause et al., 2006; Knoche et al., 2014) and mutually interacts with nearly all other J2000 process modules (Fig. 6; Knoche et al., 2014). Spatial model units contain two soil storages: the mid-size pore storage (MPS) represents the effective field capacity water budget that is reduced by the AET only. The large pore storage (LPS) cannot hold water against gravity and therefore 'is considered as the source of all subsurface flow processes in the J2000 model' (Krause et al., 2006; Knoche et al., 2014). Infiltration water is distributed to the MPS and the LPS based on a distribution coefficient until these storages are filled or the maximal infiltration rate is reached. Infiltration excess water is stored as depression storage (DPS) at the surface. When DPS is exceeded, surface runoff is generated and routed to the adjacent downslope spatial unit. The LPS outflow is distributed into lateral runoff and percolation depending on the slope and a calibration parameter. There are two groundwater storages for each spatial model unit, one having a quick hydrological reaction and one having longer residence times. The percolation water is distributed between the two groundwater storages depending on a calibration parameter and the slope (Krause et al., 2006; Knoche et al., 2014). The J2000 runoff concentration and flood routing is calculated for the spatial model units and a network of river reaches. Lateral flows calculated for each grid cell are passed to downslope grid cells until a river reach is connected, where the lateral runoff is transmitted to the streamflow budget. 'Flood routing in the river network is calculated by a simplified kinematic wave approach, using Manning's formula to calculate flow velocity' (Krause et al., 2006; Knoche et al., 2014). For the Verlorenvlei and Gaborone Dam catchments, the routing mechanism between spatial entities was switched from single- to multi-flow routines in order to more precisely capture the spatial variability within the flat terrain (Pfennig et al., 2009).

Further individual adaptations implemented to represent the specific conditions in the study areas (contour farming, irrigation agriculture, farm dams, and flood plains) are described in the following subsections.

In order to provide an easy and user-friendly way to set up such a model, software toolsets like the RBIS (River Basin Information System; Zander & Kralisch, 2016) and the GRASS-HRU (Schwartze, 2008; Schwartze et al., 2012), service- and web-based tools for geo(-data) processing, were used to provide a data basis and generate input data for the JAMS/J2000 modelling system.

Contour farming

To incorporate the effect of the locally applied land use management practice of contour bank farming, a contour bank module according to Steudel et al. (2015) was integrated. This involves the addition of contour bank storages to each HRU. The volume of this storage depends on the contour length per HRU and a predefined catchment-specific mean height of the contour bank wall. The total length per HRU is calculated during the pre-processing HRU delineation (Pfennig et al., 2009) and depends on site-specific conditions, such as slope and land use. The main inflows into the contour bank storage are surface runoff and sub-surface runoff (interflow) (Steudel et al., 2015). The proportion of surface runoff which exceeds the maximum storage capacity of the contour bank is routed as surface runoff into the next neighbouring HRU. The proportion of interflow flowing into the storage is a function of the actual interflow and a gradient (difference between water level of the saturated soil zone with the ditch and the actual total water level of this zone). Water in the ditches infiltrates and/or percolates into the underlying soil or groundwater zone. For channel drainage, each HRU with assigned contour banks is routed to the stream network according to the calculated flow accumulation. To build contour banks, guidelines for the Western Cape region (Mathee, 1984) recommend to farmers that the distance between contour banks should be planned according to:

$$\boldsymbol{V = 0.25 \times S + 0.5}$$

with

V = Vertical distance of contour banks [m]

S = Slope [%]

A detailed description of the contour bank extension can be found in Steudel et al. (2015). Within this study, adaptions were made in the delineation of the contour banks, which were then used by the model. Contrary to the parameters used by Steudel et al. (2015), the values were adapted according to the equation above. In order to fit the special circumstances in the Verlorenvlei area, the total contour bank length per HRU from different delineations using various parameter combinations was compared to the real length from digitised contour banks utilising Google Earth. The parameters described in the following equation show the best fit between modelled and real contour lengths:

$$\boldsymbol{V = 0.6 \times S + 0.5}$$

Irrigation

In order to represent water abstractions for irrigation in the model, a simulation approach that is applicable in situations where only limited information is available about the exact location and irrigation water amounts was needed. As a test case, the Verlorenvlei catchment with its large proportion of irrigated agricultural land use was chosen. In the model, the principle method of representing irrigation followed a three-step approach (Branger et al., 2016):

1. Calculate irrigation demand for all HRUs that feature irrigated agricultural land use at the current time t. This is done in two steps:
   a. Calculate the evapotranspiration deficit ($etDef_s$) between actual ($actET_s$) and potential ($potET_s$) evapotranspiration at each HRU s as
   $$etDef_s = actET_s / potET_s$$
   and compare it to a defined irrigation threshold (iT), which controls whether irrigation is used at all. For this purpose, which proportion of the actual evaporation is actually used (actET/potET) is calculated. If this proportion is below the threshold, irrigation is used. For example, a value of 0.9 for the threshold means that irrigation will be active if less than 90% of the potential evaporation is currently occurring. If $etDef_s$ is smaller than iT, continue with step b.
   b. Calculate the actual demand ($iDemand_s$) based on the actual ($actSW_s$) and maximum ($maxSW_s$) soil water storage at HRU s according to
   $$iDemand_s = cf\,(maxSW_s - actSW_s)$$
   with cf as a correction factor, which is a simple multiplier and calibration parameter that can be used to adapt the identified irrigation needs. The basis for this is initially the difference between current and maximum soil water storage. This difference is then multiplied by cf to determine the demand.
2. For each sub-basin B, sum up the irrigation demand ($iDemand_B$) for all HRUs
   $$iDemand_B = \Sigma_{s\in B}\, iDemand_s$$
   Then calculate the amount of irrigation water ($iVolume_B$) based on the available water in the stream segment ($streamVolume_B$) during the current model time step
   $$iVolume_B = \min\,(iDemand_B, streamVolume_B)$$
   and distribute the irrigation water to all demanding HRUs s proportional to their demand ($iDemand_s$).
3. At the next time step $t+1$, apply the irrigation water $iDemand_s$ at each HRU s according to a defined application procedure.

In order to allow for different types of irrigation in the test region, three optional application procedures were implemented in the model:

1. Sprinkler irrigation: precipitation is increased by the amount of irrigation water
2. Flood irrigation: net precipitation is increased by irrigation water amount (i.e., interception is not considered)
3. Dripper irrigation: the middle pore storage is increased by irrigation water amount (i.e., interception and infiltration are not considered)

As a general means to control where irrigation is possible, HRUs with irrigated land use were individually flagged. This included all areas which were designated as cultivated areas in the HRU parameter data set. For our study basin, sprinkler irrigation was used.

Farm dams

Due to the small number of climate stations, only sketchy data were available as input for hydrological modelling. Additionally, these time series are affected by numerous large gaps. As there was no measured runoff data available for calibration purposes, calculated monthly inflow values to the Gaborone Dam as stated by DWA (2006) were used in order to simulate seasonality and magnitudes of runoff. In order to capture the impact of small farm dams on runoff and storage patterns within the model, a concise analysis of existing dams in terms of location and capacity was carried out. This resulted in the assessment of 20 dams in total. Here, only those dams that are assumed to have the potential to create a noticeable impact on the overall runoff regime (i.e., dams with an area of more than one hectare) were chosen by digitising their position in Google Earth. For these 20 dams, information about capacity and overall volume was made available through DWA (1992, 2014). Furthermore, around 217 small dams with minor relevance were each considered throughout the catchment (DWA, 2014b). For each of these dams, the related river segment was identified and labelled to derive zonal statistics for capturing their location within the catchment.

Making use of this information, a new module for farm dam simulation was then implemented into the JAMS/J2000 hydrological model. Accounting for the fact that precise information is often missing, especially with regard to smaller farm dams, this approach allows simulation of the function of farm dams in a conceptual way. Here, it can be used to either represent single, large dams or a larger number of small dams belonging to a certain subwatershed as a lumped unit. The impact of the dam is simulated at the associated river reach in the following way:

1. If dam storage volume is available: extract a defined proportion of the overall reach runoff in the current time step and store the water in the dam, taking the maximum dam storage volume into account
2. At the beginning of the rainy season, empty a certain amount of the dam storage volume, thereby representing the water use over the year.

Using this simplified representation of dam operation, a dam can extract water amounting to its full volume only once a year. The water is then completely removed from the hydrological system, not taking into account its possible use for irrigation agriculture which, in theory, could mean that the stored water enters the hydrological cycle again. However, both assumptions are in line with investigations of dam operation and use of stored water. In order to account for the various unknown und uncertain parameters (e.g., individual dam volumes, operation details, water use), various parameters of the dam simulation module (e.g., amount of water used, dam volume) can be adapted for calibration based on observations. Using this new simulation module, the number of dams, their capacity, and thus their impact on runoff generation can be easily increased or decreased in order to adapt the model to any conceivable scenario.

Flood Plains

A floodplain simulation extension (J2000-Flood), characterised as a conceptual and easily transferable approach that is less data hungry and easy parameterisable, is used to simulate wetland inundation within the model. Due to the data-scarce situation in remote catchments, the extension's parameters (HRU elevation and river width) were obtained from remote sensing data only. On an iterative basis, the water height in each river segment is compared to the elevation of its neighboring HRUs. When the river segment's water level is higher (i.e., flooding occurs), the water is transferred to the HRUs and their topologically connected neighbours until the simulated flood level is too low to spread any further (Fig. 7).

Within the model, the distributed water volume is stored in the excess depression storage, interacting with soil and atmosphere, which allows evapotranspiration and infiltration to be modelled. Hence, the model is able to represent the annual flow and flood regime of the system and thus to address the effect of climate change and upstream land use changes on the flow regimes in the downstream watershed. In order to provide a spatial basis for model validation and calibration (in addition to gauge data), the inundated area was determined using the Desert Flood Index (DFI; Baig et al., 2013), which was generated from a time series of 14 Landsat image mosaics and is defined as:

$$\mathrm{DFI} = \frac{\mathrm{pGreen} - \mathrm{pSWIR} + 0.1}{(\mathrm{pGreen} + \mathrm{pSWIR})(\mathrm{NDVI} + 0.5)}$$

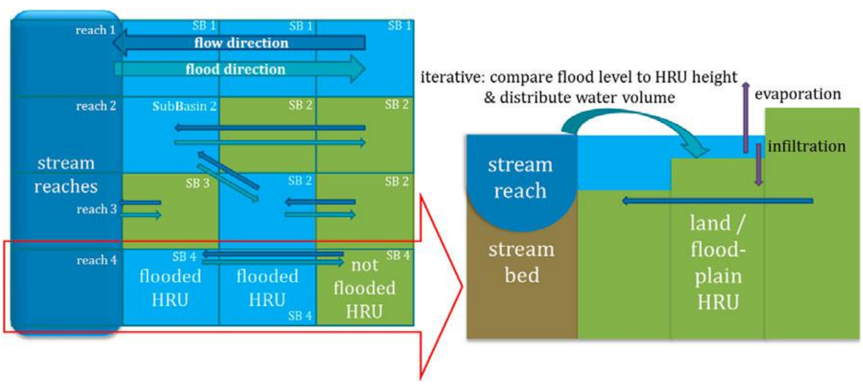

Figure 7: Schematic concept of the extension J2000-Flood in top (left) and profile view (right).

where NDVI is the Normalized Difference Vegetation Index and ρNIR, ρRed, ρGreen, and ρSWIR are the values of reflectance for the respective bands. As underflooded vegetation occurs frequently in the inundated areas, the DFI was chosen because it is better in the distinction of water and vegetation as well as bare soils compared to other indices (Baig et al., 2013; Wang et al., 2013). Moreover, it was successfully applied in the neighbouring Barotse floodplain (Zimba et al., 2018).

	e1	e2	Runoff [mm]
Without adaptions	0.48	0.42	22.413
Irrigation active	0.53	0.51	20.749
Contour farming active	0.55	0.56	18.238
All active	0.56	0.59	16.984

Table 1: Quality measures (Nash-Sutcliffe efficiency: e2, modified Nash-Sutcliffe efficiency: e1; Krause et al, 2005) and runoff produced by every implementation for the example period 01/01/1992 – 31/12/1992

Results

Verlorenvlei

A detailed description of the J2000 model applied to the Verlorenvlei catchment as well as its calibration and validation is shown in Watson et al. (2018) and Miller et al. (2018). Results of modelled runoff for the year 1992 (Fig. 8) is shown separately for the basic J2000 implementation ('natural hydrology'), implemented contour farming, and irrigation. The influence of irrigation and contour farming practices could be identified, particularly during the period from June to August, which experiences high rainfall and discharge events. During the peak period in July 1992, when the new implementations were active, the model showed less overestimation of runoff. This was also observed for low discharge periods. Regarding the quality measures (Tab. 1), it is obvious that the new implementations increase the model performance for high (Nash-Sutcliffe efficiency: e2; Krause et al., 2005) and low flow periods (modified Nash-Sutcliffe efficiency: e1; Krause et al., 2005) because runoff and, therefore, its overestimation is reduced.

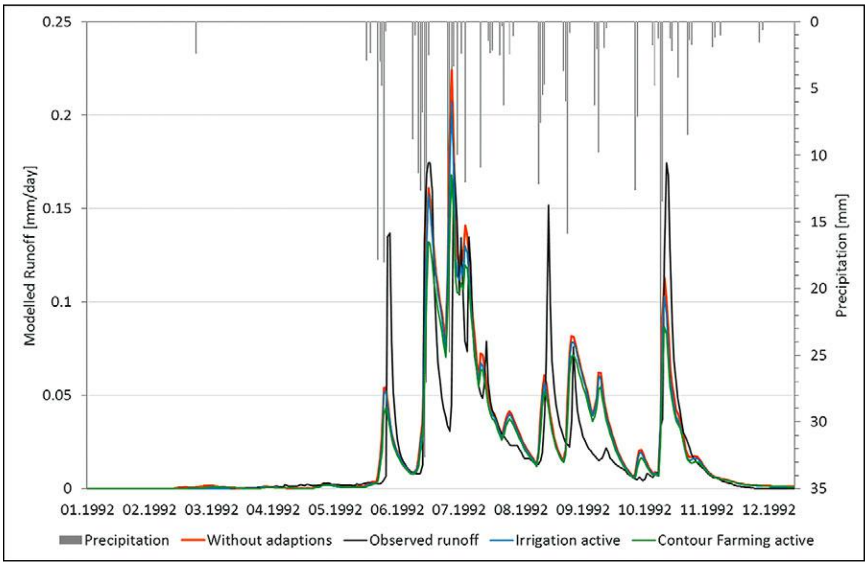

Figure 8: Rainfall, observed (grey) and simulated runoff (no adaptions made in orange, with contour farming active in green, with irrigation active in blue) for example period 01/01/1992 – 31/12/1992.

The influence of the two components becomes much clearer when examining Figure 9. Overestimations of runoff in low flow months could be minimised by using the new implementations as evidenced by the peak discharges in August and September, which were less overestimated when the model used the implementations. Minimal differences between the original model and the model with active irrigation from June to July occur because irrigation only takes place if there is demand for irrigation. Reduction of runoff is due to the decrease in overland flow, with a higher influence when contour farming is active.

Gaborone Dam

When the model was adapted to the local study area conditions and operating without the implementations of the new farm dam module, reliable results regarding the representation of all hydrologically

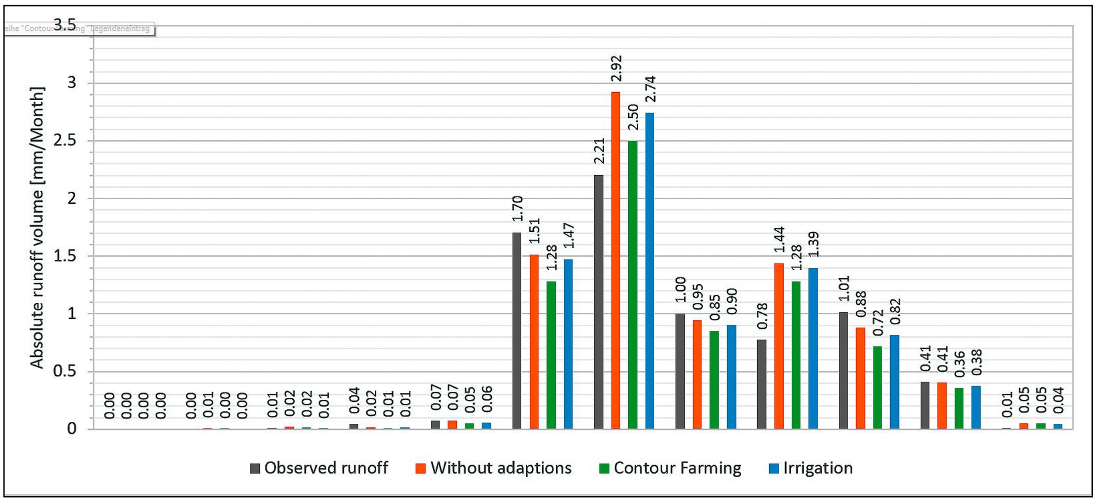

Figure 9: Monthly observed (grey) and simulated runoff (no adaptions made in orange, with contour farming active in green; irrigation active in blue) for example period 01/01/1992 – 31/12/1992.

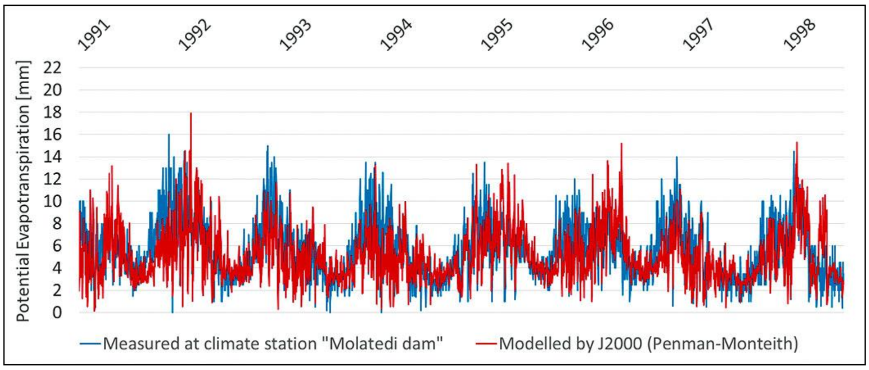

Figure 10: Comparison between measured and modelled daily potential evapotranspiration values from 1991-1998; measured values (blue) refer to Moladeti dam climate station, red line shows modelled evapotranspiration as calculated by J2000 using Penman-Monteith.

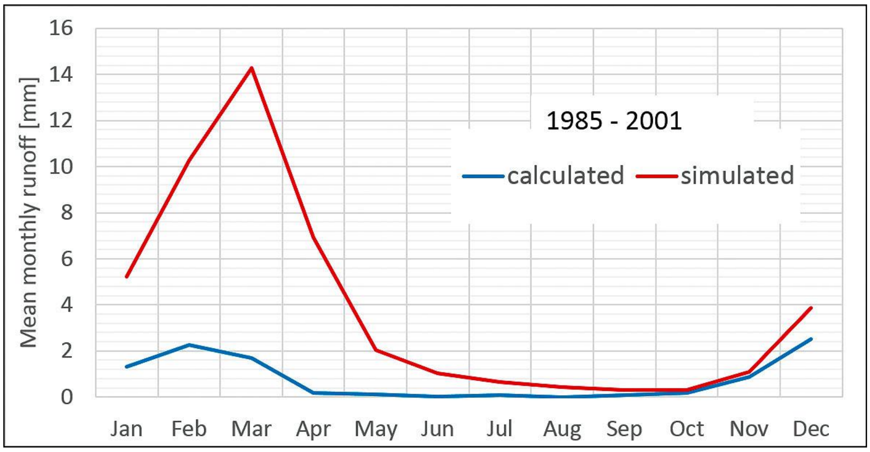

Figure 11: Comparison of mean monthly runoff; red line shows modelled values by J2000, blue line shows calculated values as stated by DWA (2006).

relevant processes such as evapotranspiration were obtained. Evapotranspiration is classified as a process having a high influence on runoff processes (Hughes, 2007). For instance, Figure 10 shows the modelled potential evapotranspiration (potET) values as calculated by J2000 using the Penman-Monteith method, compared to measured values from an A-pan at the climate station Molatedi Dam (DWA, 2014a) for the years 1991–2001. Modelled potET values showed a mean annual evapotranspiration of 1 800 mm, compared to 2 200 mm at Molatedi Dam Station. The lower potET values can be explained by vegetation dynamics represented in the model. In the first half of the rainy season, the vegetation starts to grow and the leaf area is not fully established, resulting in a reduction of the calculated potET. This dynamic cannot be represented by the measurements with an A-pan.

Simulated runoff (1985–2001; Fig. 11) fails in part to demonstrate reliable performance, but regarding the months June to December, the performance is acceptable compared to calculated values as stated by DWA (2006). These values are long-term monthly means, about which we have no detailed or quality information. Considering this data availability, reliability, and model performance, it was neither useful nor even possible to calculate any quality measures as was done for the other catchments in this study. Peak runoff values (i.e., during the rainy season from January to April) are overestimated by the model, with the highest overestimation observed for the month of March. This is due to the strong response of J2000 to high and sufficient rainfalls which occurred in the years 1988, 1991, and 2000. For these years, the model showed a strong overestimation, initiated mainly through long and strong retention periods following the peak runoff, triggered by intensive rainfalls. In addition, potential evapotranspiration showed comparatively low values during these years.

The impact of more than 200 farm dams for two representative years for notable dry (a) and wet (b) conditions within the catchment (Fig. 12) showed that using the farm dam extension, simulated runoff decreased in a distinctive way. When the runoff was compared with the initial model, the results showed that runoff had decreased by 19.4% and 6.8% for the dry and wet conditions, respectively. Regarding the modelling for the whole period, values for wet years achieved 14.7% and 17.1% for dry years. Taking a closer look to the water balance for the sub-catchment where the farm dam module was used (1985–2001), the runoff from this area decreases by 29% if farm dams are taken into account. This corresponds to 10% of the precipitation, whereas without farm dams, 14% of the precipitation were modelled as runoff.

Luanginga

After calibration using gauge data for the period of 1959–1968, relatively good results were achieved (Nash-Sutcliffe

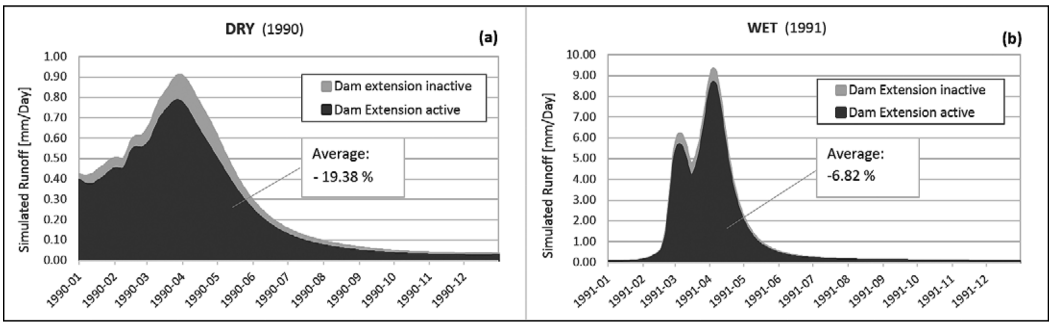

Figure 12. Simulated runoff comparison for the Gaborone Dam catchment between representative years of (a) dry (1990) and (b) wet (1991) conditions, simulated runoff without the dam extension (grey), and simulated runoff with the dam extension (light grey).

efficiency: e2 0.81; relative percentage volume error: PBIAS -4.29). Model results for the validation period, from 1981–2003, were also acceptable, with an e2 of 0.75 and a very good PBIAS of -1.29. Similar values were obtained using the modified e2, which is more sensitive to low flows: e1 0.69 for the calibration period, and e1 0.6 for the validation period. However, Figure 13 shows some shortcomings regarding the simulation of peak discharge, which is either under- or oversimulated for many years. Regarding the water balance of the validation phase (1981–2003), 93% of the precipitation evapotranspirates and only about 5.4% drains to the catchment outlet. In this context, it is interesting to note that 20% of the precipitation percolates first, but due to capillary rise and the implemented inundation, it is able to evapotranspirate later.

The validation of the spatial flood extent in total also resulted in a good correlation ($R^2 = 0.71$) between the inundated area derived from the DFI and the modelled flood area. The accuracy of the spatial distribution of the inundated area was obtained by calculating the area under the curve (Fig. 14). For example, 10% of the highest DFI values correspond to 80% of the modelled inundation in 1992. In total, the results range from an outlying value of 0.59 up to a promising 0.88. In addition, the more detailed spatial pattern also appears acceptable, resulting in an accurate simulation of the inundation in the main floodplain in most years. Considering the elevation uncertainty inherent to the digital elevation model, as well as data sparsity in terms of both time series length and station presence and location, the results are deemed satisfactory. More details about the used data sets, model calibration, and validation, as well as further results, are shown in Meinhardt (2017).

Overall, the model is able to accurately represent the annual flood regime of the system, and thus to address the potential effect of various climate change scenarios on the hydrological processes in the watershed. Under the RCP 8.5 scenario, using input data from the EC-Earth and ECHAM models and following a process of downscaling using the REMO model and bias correction, the model results revealed a substantial decrease

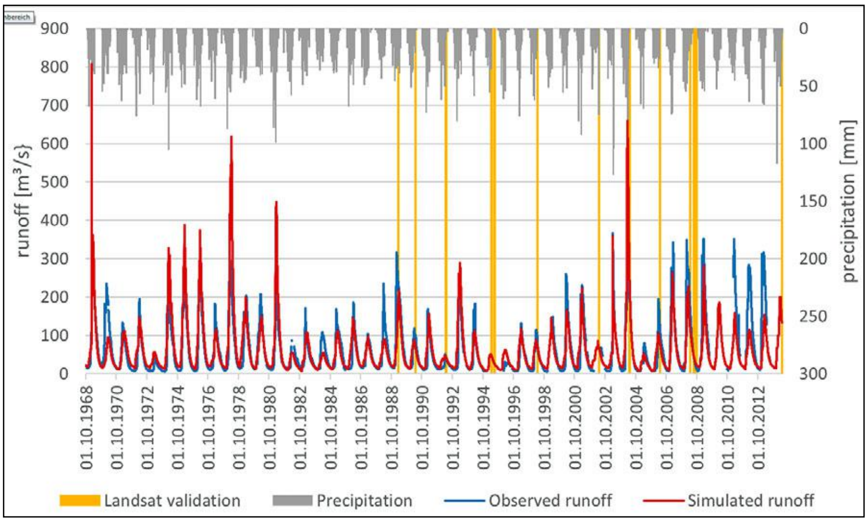

Figure 13: Observed vs. simulated runoff at the gauge in Kalabo (validation period 1981-2003) with DFI years marked).

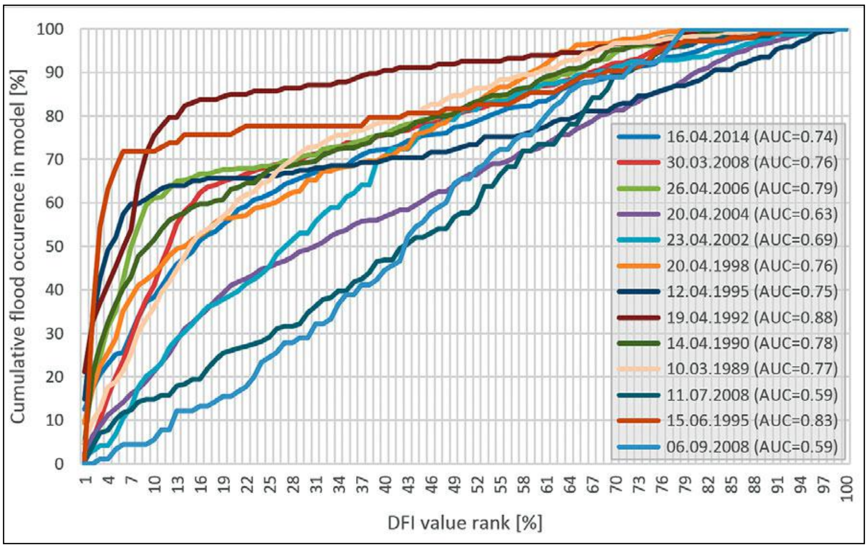

Figure 14: Area under the curve of the simulated flood extent (y-axis cumulated) compared to the derived DFI area (x-axis ranked) for the Luanginga catchment.

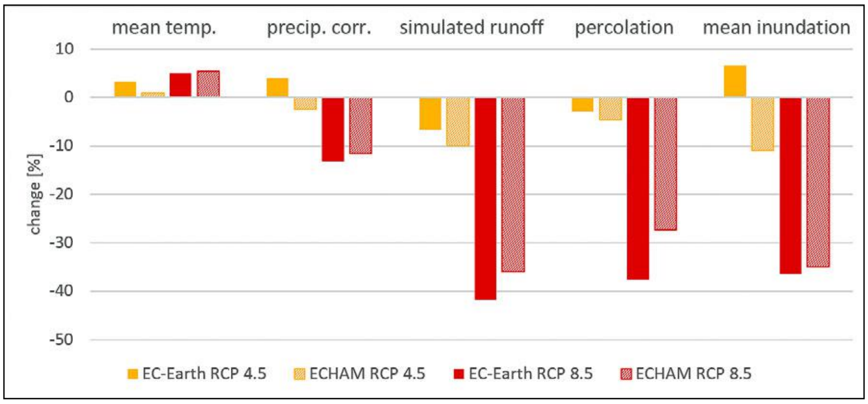

Figure 15: Percent change of precipitation, runoff, percolation, inundation extent, and temperature (change in °K) from 1986-2005 (historical) to 2081-2100 (RCP) for the Luanginga catchment.

in both runoff generation (39%) and and percolation (32%), providing an indicator for groundwater recharge being very likely (Fig. 15). The model also allows a spatially distributed output of all hydrological components like percolation as represented in Figure 16, showing areas of higher decreases particularly in the floodplain. The changes presented by these models are mainly attributable to a substantial temperature rise of about 5°C, leading to a strong increase in evapotranspiration occurring until the end of the century. The decreases in water quantity as predicted by the models used would result in a reduction of flood extent (35%) and duration and, thus, alteration and damage to the highly productive and valuable wetland ecosystem. This, in turn, would signify increased risk to the people living in the region, many of whom depend upon the wetlands for their livelihoods.

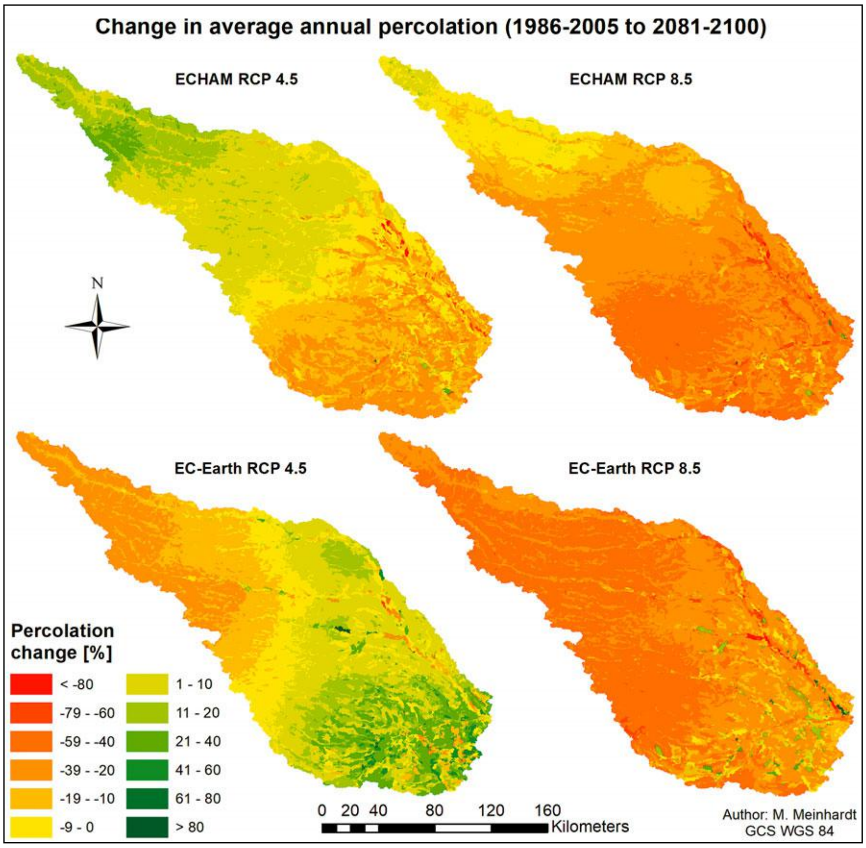

Figure 16: Average percolation (1986-2005 compared to 2081-2100) for the Luanginga catchment.

Discussion

The modelling results show a number of shortcomings, which are addressed in the following discussion. First of all, it must be appreciated that the locations of the climate stations used for the Luanginga and Verlorenvlei model are not ideal. Available stations which matched the calibration timeframe of the measured runoff and quality requirements are located far outside the catchment; for instance, the modelling of the Luanginga catchment relies mainly on the climate station in Mongu, which is situated about 60 km outside of the catchment. However, the distance to the headwaters is more than 400 km (Fig. 1). According to Wheather (2008), model performance decreases with increasing distance from climate stations to the designated catchment, which could explain why the Luanginga model failed to simulate peak discharge in many years. Additionally, nearly all climate series contained large gaps, so only a few stations could be used for modelling. Filling such gaps using other stations was not possible, as data gaps often occurred within the same time. Another limiting factor for model performance is the fairly uniform topography towards the outlet, which leads to very slow velocities, changes in flow directions, and bi-directional channels (VerWest, 2002; Druid, 2017). Furthermore, the water is not necessarily flowing in the direction of the steepest surface slope represented by the digital elevation model used, although this is assumed by the model and the HRU concept, as it was originally developed for areas with steeper gradients.

Focusing on the overestimation of runoff in the Gaborone Dam and Verlorenvlei catchments, it must be mentioned that surface runoff in semi-arid regions is primarily of Horton's type (Smith & Goodrich, 2005). This arises as a result of convective precipitation events whose intensities exceed the infiltration capacity of the soils (Pilgrim et al., 1988). Additionally, it is well known that the infiltration conditions of soil are highly variable in space and time due to processes like crusting. These are hard to represent in a hydrological model, especially on the meso and macro scales (Adornis et al., 2014). Excess water that cannot infiltrate into the ground accumulates on the surface and may subsequently lead to fast runoff (Gupta, 2010). The occurrence of this infiltration-excess overland flow is caused by the patchy vegetation cover on slope areas and shallow, poorly developed soils with low infiltration capacity, in conjunction with rigidities of the upper soil horizon (Hughes, 1995; Beven, 2002; Wheater, 2008). Accordingly, it can be assumed that surface runoff from Horton's type, particularly due to convective rainfall events during the rainy season, often does not reach the receiving water or the outlet. The precipitation events are localised and, thus, cause a reduction of water reaching the outlet as a result of infiltration excess at inclined surfaces (Hughes, 1995). Another limiting factor can be seen in so-called transmission losses (Graf, 1988), wherein large quantities of water are lost through infiltration losses in the porous and dry riverbed on their way to the catchment outlet. Following Hughes (1995), often only runoff which was generated by large-scale rainfall events or by directly successive rainfall events reaches the outlet. Another limiting factor regarding peak runoffs may result from the relatively flat terrain characteristics within the catchments. Flat terrain often leads to wider areas being available for runoff processes, leading to a temporal retention of runoff, in turn leading to pronounced retention periods (Pan et al., 2012), also shown within this study.

Looking at the numerous dams of the Gaborone catchment, it is of great importance to model the evapotranspiration correctly. According to Adams et al. (1999), the modelled evapotranspiration values are within range, considering the interpolation of climate input values over the catchment area compared to measured values at one specific climate station.

Some studies indicate that the decline of the volume of water is supported by the construction of several small farm dams upstream of the Gaborone Dam; these are used for watering livestock and for irrigation (Meigh, 1995; DWA, 2014b). Combined with the spread of arable land and meadows, the influence of the farm dams on the water balance increases (DWA, 1992; Meigh, 1995; Plessis & Rowntree, 2003). A number of case studies have shown that smaller farm dams can affect the flow pattern of a basin. Habets et al. (2014) revealed that accumulated water for irrigation is not available for runoff processes and reported a decrease in the outflow in presence of farm dams. Studies in South Africa confirmed the influence of farm dams on flow patterns (Hughes & Mantel, 2010; Mantel et al., 2010), particularly affecting the base flow. Meigh (1995) discussed the impact of smaller farm dams on the flow patterns and its relevance for inflow into the Gaborone Dam. He came to the conclusion that the construction of additional farm dams may cause a severe threat to the functioning of the dam as a viable water supply for Gaborone. The study showed that the farm dams had a complete capacity of 10% of mean annual runoff. Meigh (1995) stated that the total runoff volume of a catchment is also reduced by approximately the same amount. Additional factors such as location of the dams were identified as controls, as an increased impact on downstream areas was shown by increased inflow volumes to these dams (Meigh, 1995). Meigh also confirmed a greater impact of dams in drought years. Furthermore, the study indicated that a small number of large farm dams has less impact on the runoff than a higher number of small dams. This is due to the smaller surface area of larger dams in relation to their capacity, resulting in reduced evapotranspiration values.

The modelling results of the present study support the assumption of Habets et al. (2014) and Meigh (1995) of a notable influence of farm dams in dry years. Overestimation of runoff during the wet season was reduced after the implementation of the farm dam module, but was still present. Reasons for this observation can be seen in the lack of representation of runoff in very shallow areas with low slope and a partial under-representation of evapotranspiration. Furthermore, only calculated monthly values were available for direct model calibration, as well as short runoff time series of adjacent areas. Errors may arise here from comparing values from the calculation and from adjacent basins, as these sides partly exhibited steeper slopes and showed some notable differences in catchment size compared to the Gaborone Dam catchment.

Comparing the contour bank model extension of Verlorenvlei catchment with other studies, it is obvious that very few examined the implementation of contour banks in distributed hydrological models. For instance, Quessar et al. (2009) investigated the impact of earthen dikes on hydrological conditions in a Tunisian catchment by utilising the SWAT hydrological model (Arnold et al., 1998). The LAPSUS model was successfully applied by Lesschen et al. (2009) in the semi-arid Carcavo catchment in southeast Spain, showing that the spatial distribution of agricultural terraces determined hydrological connectivity at the catchment scale. Steudel et al. (2015) investigated the use of the hydrological model J2000 and the influence of contour banks on the hydrology and sediment transport in the Sandspruit catchment in South Africa. All three studies clearly indicated that contour farming has an influence on hydrological process dynamics and should be integrated into distributed hydrological models whenever such practices are apparent in a semi-arid catchment.

Different model types are available to integrate irrigation into hydrological modelling. Hagi-Bishow and Bonnell (2000) assessed the usability of the numerical LEACHM-C Model for semi-arid saline irrigation, resulting in the usability in poor-quality water catchments. The lumped, conceptual catchment model GR4J tested the reliability of low-flow simulations in a semi-arid Andean catchment facing climate variability and water-use changes (Hublart et al., 2015). This study resulted in confirming the model's applicability to assess the capacity of the system to meet increasing crop water needs. However, few studies used irrigation mechanisms as input to distributed hydrological models. As one example, Ahmed et al. (2011) applied the SWAT model (Arnold et al., 1998) in a Mediterranean catchment to a sprinkler irrigated watershed. They indicated the usability of distributed models for a simulation of irrigation demands.

Focusing on the Luanginga catchment, other studies show a very similar behaviour for the Upper Zambezi regarding the hydrological process dynamics (Bastiaansen, 1995; Gerrits, 2005; Winsemius et al., 2006; McCartney et al., 2013). Compared to other studies, none of these presents a model which maps the hydrological processes spatially distributed in a high degree of detail as well as for larger catchments of more than 10 000 km². These studies typically rely on in-situ measurements (Hunter et al., 2007; Pramanik et al., 2010) or model only smaller (27 km²; Adams et al., 2016) isolated wetlands or flooded areas (Thompson et al., 2004; Zhang & Mitsch, 2005; Fernández et al., 2016). This clearly shows the need and the importance of the developed flood extension, which creates a hydrological model system meeting the requirements mentioned above. Furthermore, this extension is parameterisable with remote sensing data, such as the SRTM-DGM, in order to simulate the flooded area and its depth and duration even in data-poor areas.

At the same time, input data like precipitation from the distant station in Mongu and especially the height accuracy from the elevation model account for major uncertainties of the presented modelling results. The SRTM-DGM employed is supposed to have an average height accuracy of approximately 3.1–4.4 m (RMSE 12.4–16.5 m) for areas with a slope less than 10° and grass and scrubland, which is typical for the catchment (Tighe & Chamberlain, 2009). To keep the impact of this height accuracy in the inundation modelling small, a spatial mean of the elevation was calculated for each HRU, which reduces the inaccuracy (Jung & Jasinski, 2015).

For the climate change analysis, a slight decrease in the precipitation is expected, but a more important effect from the rising temperatures will be increased evaporation and thus a reduction of the average annual runoff by 42 (EC-Earth RCP 8.5) and 36% (ECHAM RCP 8.5). Other studies also project declining flows in the region (Wolski et al., 2012; Kling et al., 2014; Zhao & Dai, 2015), which have already been confirmed by past hydrological measurements (Gaughan & Waylen, 2012). For example, values between 17–26% are given for the reduction of the mean discharge in the neighbouring Okavango (gauge Mukwe) up to the end of the century (Andersson et al., 2006; Todd et al., 2008). Kling et al. (2014) used EU WATCH data to model a decrease of up to 18% for the same period across the entire Zambezi. These values are lower in comparison with the study area of this work. The reason for this is probably the comparatively higher evaporation in the Luanginga. This is due to the larger proportion of the flood area to the respective catchment area size. In addition to the different catchment areas, the studies also used different climate models, scenarios, and hydrological models, which makes it difficult to compare them with each other. Together, however, they all result in strongly decreasing discharges until the end of the century. In addition, climate projection data include some uncertainties, especially under the unstable conditions of the tropical and subtropical atmosphere.

Moreover, the pilot catchment and its adapted models show the benefits of integrated distributed models because they provide a way to describe spatio-temporally variable hydrological processes including the influences of human activities as well as effects of climate change. For a realistic representation of prevailing human activities combined with natural hydrologic dynamics, the model employed should be process-based, i.e. able to reproduce lateral and vertical processes (Hughes, 2004; Arnold & Fohrer, 2005;). The use of a spatially distributed model in this study showed advantages in accurately representing the localisation of the farm dams and therefore their different influences on the runoff processes. The same is true for the reliable representation of climatic conditions, evapotranspiration, and groundwater recharge, as well lateral soil water processes.

Overall, transferability is ensured due to the fact that the implementations of inundation, farm dams, and irrigation simulation are developed in a conceptual way so they can be applied in other catchments, especially if data availability represents a constraint for the correct simulation of rainfall runoff mechanisms when human influences are present. The possibility of transfer is also given for the contour banks module. However, while delineating the location and number of contour banks, specific conditions in the respective catchments must be carefully considered (for example, land use forms, slope).

Conclusions

For all three pilot catchments in southern Africa, it has been shown that the selected approach of an adapted hydrological model is suitable to address the formulated problems. Additionally, the conceptual adaption approach used shows two advantages. First, the models can be applied in data-scarce regions; second, this allows transferability under similar conditions without work-intensive adaptions being necessary. For example, the flood implementation is currently applied in the upper Okavango River Basin. Moreover, it became obvious that it is necessary to adapt hydrological models to specific hydrological conditions on the catchment scale to model the hydrological processes and therefore the water balance correctly. Hence, the adapted models presented here make a valuable contribution to properly quantifying the impacts of changing climate and land management on hydrological process dynamics.

Acknowledgements

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References

Adams, W. M., Goudie, A. S. & Orme, A. R. (Eds.) (1999) *The Physical Geography of Africa*. Oxford Regional Environments, Oxford.

Adams, J.M., Gasparini, N.M., Hobley, D.E.J., Tucker, G.E., Hutton, E.W.H., Nudurupati, S.S., & Istanbulluoglu, E. (2016) The Landlab Overland Flow component: A Python library for computing shallow-water flow across watersheds. *Geoscience Model Development Discussions*, 1–34.

Ahmed, S., Dechmi, F. & Javier, B. (2011) Application of SWAT model to a sprinkler-irrigated watershed in the middle Ebro River Basin (Spain). The 2011 International Soil and Water Assessment Tool Conference, Toledo, Spain, 135–150.

Allgemeine Zeitung. (2016) Swakoppforte-Damm wird zur grünen Pfütze – Wasser für Karibib und Navachab. Retrieved from http://www.az.com.na/nachrichten/swakoppforte-damm-wird-zur-grnen-pftze-wasser-fr-karibib-und-navachab/

Andersson, L., Wilk, J., Todd, M.C., Hughes, D.A., Earle, A., Kniveton, D., Layberry, R., & Savenije, H.H.G. (2006) Impact of climate change and development scenarios on flow patterns in the Okavango River. Journal of Hydrology, **331**, 43–57.

Archer, E., Conrad , J., Munch, Z., Opperman, D., Tadross, M., & Venter, J. (2009) Climate change, groundwater, and intensive commercial farming in the semi-arid northern Sandveld, South Africa. *Journal of Integrative Environmental Sciences*, **6**, 139–155.

Arnold, J., Srinivasan, R., Muttiah, R. & Williams, J. (1998) Large-area hydrologic modelling and assessment. Part I, Model development. *Journal of the American Water Resources Association*, **34**, 73–89.

Arnold, J. G. & Fohrer, N. (2005) SWAT2000: Current capabilities and research opportunities in applied watershed modelling. Hydrological Processes, **19**, 563–572.

Baccari, N., Boussema, M. R., Lamachère, J-M. & Nasri, S. (2008) Efficiency of contour benches, filling-in and silting-up of a hillside reservoir in a semi-arid climate in Tunisia. *Comptes Rendus Geoscience*, **340**, 38–48.

Baig, M.H.A., Wang, S., Zhang, L., Jiang, G., Lu, S., & Tong, Q. (2013) Comparison of MNDWI and DFI for water mapping in flooding season. Geoscience and Remote Sensing Symposium (IGARSS), 2013 IEEE International, 21–26 July 2013, pp. 2876–2879,.

Water resources

Bastiaansen, C.J.M. (1995) Lui River Valley Model and some of its applications. *Rapport 55*, Landbouwuniversiteit Wageningen, Wageningen.

Beven, K. (2002) Runoff generation in semi-arid areas. *Dryland Rivers. Hydrology and Geomorphology of Semi-Arid Channels* (ed. by L. J. Bull & M. J. Kirkby.), 388. Wiley, Chichester, UK.

Branger, F., Gouttevin, I., Tilmant, F., Cipriani, T., Barachet, C., Montginoul, M., Le Gros, C., Sauquet, E., Braud, I. & Leblois, E. (2016) Distributed hydrological modelling of the Rhône river basin. http://cemadoc.irstea.fr/cemoa/PUB00051555

Conrad, J. & Munch, Z. (2006) Groundwater reserve determination required for the Sandveld, Olifants-Doorn water management area, GEOSS report no. 2005/04-20.

Druid, S. (2017) Uncertainties associated with hydrological terrain analysis in flat topography wetlands. Department of Earth Sciences, Uppsala University: Bachelor thesis.

DWA (Department of Water Affairs) (1992) A study of the impact of small dam construction on downstream water resources. *Final Report (No. 1).* DWA, Gaborone, Botswana.

DWA (Department of Water Affairs) (2006) *National Water Master Plan Review (SMEC/EHES) - Volume 3: Surface Water Resources*. DWA, Gaborone, Botswana

DWA (Department of Water Affairs) (2014a) A study of the impact of small dam construction on downstream water resources (updated). *Final Report (Draft).* DWA, Gaborone, Botswana.

DWA (Department of Water Affairs) (2014b) List of Registered Dams Jan. 2014. Government of South Africa, Capetown. Retrieved from https://www.dwa.gov.za/DSO/Documents/List%20of%20Registered%20Dams%20Jan%202014.xls

Engelbrecht, F., Adegoke, J., Bopape, M.J., Naidoo, M., Garland, R., Thatcher, M., McGregor, J., Katzfey, J., Werner, M., Ichoku, C., & Gatebe, C. (2015) Projections of rapidly rising surface temperatures over Africa under low mitigation. *Environmental Research Letters*, **10**, 1-16.

Fernández, A., Najafi, M.R., Durand, M., Mark, B.G., Moritz, M., Jung, H.C., Neal, J., Shastry, A., Laborde, S., Phang, S.C., Hamilton, I.M., & Xiao, N. (2016) Testing the skill of numerical hydraulic modeling to simulate spatiotemporal flooding patterns in the Logone floodplain, Cameroon. *Journal of Hydrology*, **539**, 265–280.

Flügel, W.-A. (1995) River salinisation due to dryland agriculture in the Western Cape Province, Republic of South Africa. *Environment International*, **21**, 679–686.

FAO Subregional Office for Southern and East Africa (2004) Drought impact mitigation and prevention in the Limpopo River Basin: A situation analysis (No. 4). *Land and Water Discussion Paper*, **160**. Food and Agriculture Organization of the United Nations, Rome.

Foley, J.P. (2008) Centre pivot and lateral move machines. *WATERpak A Guide for Irrigation Management in Cotton*, pp. 195–220. Cotton Research and Development Corporation, Narrabri, Australia,

Fotso-Nguemo, T.C., Vondou, D.A., Pokam, W.M., Djomou, Z.Y., Diallo, I., Haensler, A., Tchotchou, L.A.D., Kamsu-Tamo, P.H., Gaye, A.T. & Tchawoua, C. (2017a) On the added value of the regional climate model REMO in the assessment of climate change signal over Central Africa. *Climate Dynamics*, **49**, 1-26.

Fotso-Nguemo, T.C., Vondou, D.A., Tchawoua, C. & Haensler, A. (2017b) Assessment of simulated rainfall and temperature from the regional climate model REMO and future changes over Central Africa. *Climate Dynamics,* **48**, 3685–3705.

Fowler, H.J. & Kilsby, C.G. (2007) Using regional climate model data to simulate historical and future river flows in northwest England. *Climate Change*, **80**, 337–367.

Franke, L., Steyn, M., & Haverkort, A. (2014) Series: Potato production in a changing climate II. What are the prospects for the Sandveld? *Technical News*, CHIPS.

Gaughan, A.E., Waylen, P.R. (2012) Spatial and temporal precipitation variability in the Okavango-Kwando-Zambezi catchment, southern Africa. *Journal of Arid Environments*, **82**, 19–30.

Gerrits, A.M.J. (2005) Hydrological modelling of the Zambezi catchment from gravity measurements. Delft University of Technology, Delft; master's thesis.

Graf, W. L. (1988) *Fluvial Processes in Dryland Rivers*. Springer, New York.

Gudmundsson, L., Bremnes, J.B., Haugen, J.E. & Engen-Skaugen, T. (2012) Technical Note: Downscaling RCM precipitation to the station scale using statistical transformations: A comparison of methods. *Hydrological Earth Systems Science*, **16**, 3383–3390.

Güntner, A. (2002) Large-scale hydrological modelling in the semi-arid northeast of Brazil. University of Potsdam, Potsdam, Germany; dissertation.

Gupta, S.K. (2010) *Modern Hydrology and Sustainable Water Development*. Wiley-Blackwell, Oxford.

Habets, F., Philippe, E., Martin, E., David, C. H. & Leseur, F. (2014) Small farm dams: Impact on river flows and sustainability in a context of climate change. *Hydrological Earth Systems Science,* **18**, 4207–4222.

Hänsler, A., Hagemann, S. & Jacob, D. (2011) Dynamical downscaling of ERA40 reanalysis data over southern Africa: Added value in the simulation of the seasonal rainfall characteristics. International Journal of Climatology, **31**, 2338–2349.

Hagi-Bischow, M. & Bonell, R.B. (2000) Assessment of LEACHM-C Model for semi-arid saline irrigation. *ICID Journal,* **49**, 29–42.

Hublart, P., Ruelland, D., Garc la De Cortázar Atauri, I. & Ibacache, A. (2015) Reliability of a conceptual hydrological model in a semi-arid Andean catchment facing water-use changes. *Proceedings of the IAHS*, **371**, 203–209.

Hughes, D. A. (1995) Monthly rainfall-runoff models applied to arid and semiarid catchments for water resource estimation purposes. *Hydrological Sciences Journal*, **40**, 751–769.

Hughes, D. A. (2004) Three decades of hydrological modelling research in South Africa. *South African Journal of Science*, **100**, 638–642.

Hughes, D. A. & Mantel, S. K. (2010) Estimating the uncertainty in simulating the impacts of small farm dams on streamflow regimes in South Africa. *Hydrological Sciences Journal*, **55**, 578–592.

Hughes, D. A. (2007) Modelling semi-arid and arid hydrology and water resources: The southern Africa experience. *Hydrological Modelling in Arid and Semi-Arid Areas, International Hydrology Series* (ed. by H. Wheather , S. Sorooshian & K. D. Sharma), pp. 22-40. Cambridge University Press, Cambridge.

Hunter, N.M., Bates, P.D., Horritt, M.S., & Wilson, M.D. (2007) Simple spatially distributed models for predicting flood inundation: A review. *Geomorphology*, **90**, 208–225.

IGC (International Growth Centre). (2016) Lights out: Zambia's electricity crisis. Retrieved from http://www.theigc.org/blog/lights-out-zambias-electricity-crisis/

Jung, H. & Jasinski, M.F. (2015) Sensitivity of a floodplain hydrodynamic model to satellite-based DEM scale and accuracy: Case study, the Atchafalaya Basin. *Remote Sensing*, **7**, 7938–7958.

Kingumbi, A., Besbes, M., Bourges, J. & Garetta, P. (2004) Evaluation des transferts entre barrage et aquifères par la méthode de bilan d'une retenue en zone semi-aride. Cas d'El Haouareb en Tunisie centrale. *Revue des sciences de l´eau,* **17**, 213–225.

Kling, H., Stanzel, P., & Preishuber, M. (2014) Impact modelling of water resources development and climate scenarios on Zambezi River discharge. *Journal of Hydrology: Regional Studies*, **1**, 17–43.

Knight, D.J. (1990) The proven usefulness of instrumentation systems on varied dam projects. *Geotechnical Instrumentation in Practice: Purpose, Performance and Interpretation: Proceedings of the Conference on Geotechnical Instrumentation in Civil Engineering Projects,* pp. 401–414. Thomas Telford, London.

Knight, F.H., Conrad, J. & Helme, N. (2007) *Biodiversity Best Practise Guidelines for Potato Production in the Sandveld*. Potatoes South Africa, Pretoria.

Knoche, M., Fischer, C., Pohl, E., Krause, P. & Merz, R. (2014) Combined uncertainty of hydrological model complexity and satellite-based forcing data evaluated in two data-scarce semi-arid catchments in Ethiopia. *Journal of Hydrology*, **519**, 2049–2066.

Kralisch, S. & Krause, P. (2006) JAMS: A framework for natural resource model development and application. *Proceedings of the iEMSs Third Biannual Meeting, 'Summit on Environmental Modelling and Software'* (ed. by A. Voinov, A. Jakeman & A. Rizzoli.). Burlington, Vermont, USA. Retrieved from http://www.iemss.org/iemss2006/papers/s5/254_Kralisch_1-4.pdf

Krause, P. (2001) Das Hydrologische Modellsystem J2000. Beschreibung und Anwendung in großen Flussgebieten. *Reihe Umwelt*, Vol. 29. Schriften des Forschungszentrum Jülich.

Krause, P. (2002) Quantifying the impact of land use changes on the water balance of large catchments using the J2000 model. *Physics and Chemistry of the Earth, Parts ABC,* **27**, 663–673.

Krause, P., Bäse, F., Bende-Michl, U., Fink, M., Flügel, W. & Pfennig, B. (2006) Multiscale investigations in a mesoscale catchment: Hydrological modelling in the Gera catchment. *Advances in Geosciences*, **9**, 53–61.

Krause, P., Boyle, D.P. & Bäse, F. (2005) Comparison of different efficiency criteria for hydrological model assessment. *Advances in Geosciences*, **5**, 89–97.

Kusangaya, S., Warburton, M.L., Archer van Garderen, E., & Jewitt, G.P.W. (2014) Impacts

of climate change on water resources in southern Africa: A review. *Physics and Chemistry of the Earth*, **67–69**, 47–54.
Lesschen, J. P., Schoorl, J. M. & Cammeraat, L. H. (2009) Modelling runoff and erosion for a semi-arid catchment using a multiscale approach based on hydrological connectivity. *Geomorphology,* **109**, 174–183.
Mantel, S. K., Muller, N. W. & Hughes, D. A. (2010) Ecological impacts of small dams on South African rivers Part 2: Biotic response: Abundance and composition of macroinvertebrate communities. *Water SA,* **36**, 361–370.
Mason, S.J. & Jury, M.R. (1997) Climatic variability and change over southern Africa: A reflection on underlying processes. *Progress in Physical Geography*, **21**, 23-50.
Mathee, J. A. La G. (1984) Beskerming van Bewerkte Landerye. *National Soil Conservation Manual.* (Directorate of Agricultural Engineering and Water Supply), chapter 8. Goverment Printer, Pretoria, South Africa.
Mazvimavi, D. & Wolski, P. (2006) Long-term variations of annual flows of the Okavango and Zambezi Rivers. *Physics and Chemistry of the Earth*, **31/15**, 944-951.
McCartney, M., Cai, X., Smakhtin, V. (2013) Evaluating the flow regulating functions of natural ecosystems in the Zambezi River Basin. *IWMI Research Report 148*. International Water Management Institute (IWMI), Colombo, Sri Lanka.
Meigh, J. (1995) The impact of small farm reservoirs on urban water supplies in Botswana. *Natural Resource Forum,* **19**, 71–83.
Meinhardt, M. (2017) Auswirkungen des Klimawandels auf die Hydrologie im Oberen Zambezi: Ein prozessbasierter räumlich distributiver Modellierungsansatz zur Quantifizierung der hydrologischen Veränderungen unter Berücksichtigung der jährlichen Überflutung. FSU Jena: Dissertation. Retrieved from http://nbn-resolving.de/urn:nbn:de:gbv:27-dbt-20170616-1130019
Miller, J.A., Watson, A.P., Fleischer, M., Eilers, A., Sigidi, N.T., van Gend, J., van Royen, J., Butler, M., Clarke, C.E. & de Clercq, W. (2018) Groundwater quality, quantity, and recharge estimation on the west coast of South Africa. This volume.
Miola, A. & Simonet, C. (2014) *Concepts and Metrics for Climate Change Risk and Development: Towards an Index for Climate Resilient Development*. Joint Research Centre, Science and Policy Reports. Publications Office of the European Union, Luxembourg.
Mitsch, W.J. & Gosselink, J.G. (2000) *Wetlands*. John Wiley & Sons, New York.
MMEGI (2016) Gaborone Dam springs to life. Retrieved from http://www.mmegi.bw/index.php?aid=58643&dir=2016/march/17
Nasri, S. (2007) Caractéristiques et impacts hydrologiques de banquettes en cascade sur un versant semi-aride en Tunisie central. *Hydrological Science Journal*, **52**, 1134–1145.
Nciizah, A.D. & Wakindiki, I.C. (2015) Soil sealing and crusting effects on infiltration rate: a critical review of shortfalls in prediction models and solutions. *Archives of Agronomy and Soil Science*, **61**, 1211–1230.
Nel, J.M. (2004) Assessment of the groundwater potential of the Langvlei catchment with special emphasis on the protection of the water resources and management options, report no. GH-4000. Department of Water Affairs and Forestry, Pretoria, South Africa.
Nepal, S. (2002) *Evaluating Upstream-Downstream Linkages of Hydrological Dynamics in the Himalayan Region.* Friedrich Schiller University, Jena.
New York Times. (2016) Climate change hits hard in Zambia, an African success story. Retrieved from http://www.nytimes.com/2016/04/13/world/africa/zambia-drought-climate-change-economy.html?_r=0
Omary, M., Camp, C.R. & Sadler, E.J. (1997) Centre pivot irrigation system modification to provide variable water application depths. *Transactions of the ASAE*, **13**, 235–239.
Ouessar, M., Bruggeman, A., Abdelli, F., Mohtar, R.H., Gabriels, D. & Cornelis, W.M. (2009) Modelling water-harvesting systems in the arid south of Tunisia using SWAT. *Hydrology and Earth System Sciences*, **13**, 2003–2021.
Pan, F., Stieglitz, M. & McKane, R. B. (2012) An algorithm for treating flat areas and depressions in digital elevation models using linear interpolation. *Water Resources Research*, **48**.
Parida, B. P., Moalafhi, D. B. & Kenabatho, P. K. (2006) Forecasting runoff coefficients using ANN for water resources management: The case of Notwane catchment in Eastern Botswana. *Physics and Chemistry of the Earth*, **31**, 928–934.
Peel, M. C., Finlayson, B. L. & MacMahon, T. A. (2007) Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth Science Systems Discussion*, **4**, 439–473.
Pfennig, B., Kipka, H., Wolf, M., Fink, M., Krause, P. & Flügel, W. A. (2009) Development of an extended routing scheme in reference to consideration of multi-dimensional flow relations between hydrological model entities, 1972–1978. Presented at the 18th World IMACS / MODSIM Congress, Cairns, Australia. Retrieved from http://mssanz.org.au/modsim09
Pilgrim, D. H., Chapman, T. G. & Doran, D. G. (1988) Problems of rainfall-runoff modelling in arid and semi-arid regions. *Hydrological Sciences Journal*, **33**, 379–400.
Plessis, A. J. E. D. & Rowntree, K. M. (2003) Water resources in Botswana with particular reference to the savanna regions. *South African Geography Journal*, **85**, 42–49.
Potatoes South Africa. (2015) *2014/2015 Potato Industry Report*. Potatoes South Africa, Pretoria.
Pramanik, N., Panda, R.K., & Sen, D. (2010) One-dimensional hydrodynamic modeling of river flow using DEM extracted river cross-sections. *Water Resources Management*, **24**, 835–852.
Schulze, R.E. (2000) Modelling hydrological responses to land use and climate change: A southern African perspective. *AMBIO: A Journal of the Human Environment*, **29**, 12.
Schwartze, C., Kralisch, S. & Flügel, W.-A. (2012) Virtual appliances for geospatial data processing. *Proceedings of the International Congress on Environmental Modelling and Software, Sixth Biennial Meeting* (ed. by R. Seppelt, A. A. Voinov, S. Lange & D. Bankamp). Leipzig, Germany. Retrieved from http://www.iemss.org/iemss2012/proceedings/G1_2_0914_Schwartze_et_al.pdf
Schwartze, C. (2008) Deriving Hydrological Response Units (HRUs) using a web processing service implementation based on GRASS GIS. *Proceedings of the Workshop Geoinformatics FCE CTU 2008,* **3**, 67–78. Presented at the Geoinformatics FCE CTU 2008 Workshop, Technical University, Prague, Czech.
Smith, R.E. & Goodrich, D.C. (2005) Rainfall excess overland flow. *Encyclopedia of Hydrological Sciences* (ed. by M. G. Anderson & J. J. McDonnell), pp. 1707–1718. Wiley & Sons, Chichester, UK.
SREX. (2012) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* (ed. by C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, & P.M. Midgley). Cambridge University Press, Cambridge, UK, and New York, NY, USA.
Steudel, T., Bugan, R., Kipka, H., Pfennig, B., Fink, M., de Clercq, W., Flügel, W.-A. & Helmschrot, J. (2015) Implementing contour bank farming practices into the J2000 model to improve hydrological and erosion modelling in semi-arid Western Cape Province of South Africa. *Hydrology Research,* **46**, 192.
Steudel, T., Göhmann, H., Flügel, W.-A. & Helmschrot, J. (2013a) Hydrological assessment of hydrological dynamics in the upper Okavango. *Biodiversity & Ecology,* **5**, 247-261.
Steudel, T., Göhmann, H., Mosimanyana, E., Quintino, M., Flügel, W.-A. & Helmschrot, J. (2013b) Okavango Basin - Hydrology. *Biodiversity & Ecology,* **5**, 19-22.
Thompson, J.R., Sorenson, H.R., Gavin, H., & Refsgaard, A. (2004) Application of the coupled MIKE SHE/MIKE 11 modelling system to a lowland wet grassland in southeast England. Journal of Hydrology, **293**, 151–179.
Tighe, M.L. & Chamberlain, D. (2009) Accuracy comparison of the SRTM, ASTER, NED, Nextmap® USA digital terrain model over several USA study sites. ASPRS/MAPPS 2009 Fall Conference, November 16-19.
Todd, M.C., Andersson, L., Hughes, D.A., Kniveton, D., Layberry, R., Murray-Hudson, M., Savenije, H.H.G., Wilk, J., & Wolski, P. (2008) Simulating climate impacts on water resources: Experience from the Okavango River, southern Africa. *Hydrological Modelling and the Water Cycle: Coupling the Atmospheric and Hydrological Models*, pp. 243-265. Springer, Heidelberg.
van Wilgen, N.J., Goodall, V., Holness, S., Chown, S.L. & McGeoch, M.A. (2016) Rising temperatures and changing rainfall patterns in South Africa's national parks. *International Journal of Climatology*, **36**, 706–721.
ver West, J. (2002) *Hydrologic Analysis in Flat Terrain*. Texas A&M University, Department of Civil Engineering.
Wakindiki, I. I. C., Mochoge, B. O. & Semoka, J. M. R. (2007) Assessment of indigenous soil and water conservation technology for smallholder farms in semi-arid areas in Africa and close spaced trash lines effect of erosion and crop yield. *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities* (ed. by A. Bationo, B. Waswa, J. Kihara & J. Kimetu), pp. 805–814. Springer, Dordrecht.
Wang, S., Baig, M. A., Zhang, G., Jiang, L.S., & Tong, Q. (2013) Comparison of MNDWI and DFI for water mapping in flooding season. *Chinese Academy of Sciences*, 2876–2879.

Watson, A., Miller, J., Fleischer, M. & de Clercq, W. (2018) Estimation of groundwater recharge via percolation outputs from a rainfall/runoff model for the Verlorenvlei estuarine system, west coast, South Africa. *Journal of Hydrology,* **558**, 238–254.

Wheater, H. S. (2008) Modelling hydrological processes in arid and semi-arid areas: An introduction to the workshop. *Hydrological Modeling in Arid and Semi-Arid Areas* (ed. by H.S. Wheater, S. Sorooshian & K.D. Sharma), 1–22. Cambridge University Press, New York.

Winsemius, H.C., Savenije, H.H.G., Gerrits, a. M.J., Zapreeva, E. a., Klees, R. (2006) Comparison of two model approaches in the Zambezi River basin with regard to model reliability and identifiability. *Hydrological Earth Systems Science Discussions*, **2**, 2625–2661.

Wolf, M., Pfennig, B., Krause, P. & Flügel, W.-A. (2009) Delineation of topographic process entities using SRTM for hydrological modelling. *18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation* (ed. by R.S. Anderssen, R.D. Braddock & L.T.H. Newham), pp. 2021–2027. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation.

Wolski, P., Todd, M.C., Murray-Hudson, M.A., & Tadross, M. (2012) Multi-decadal oscillations in the hydro-climate of the Okavango River system during the past and under a changing climate. *Journal of Hydrology*, **475**, 294–305.

WUC. (2014) *Dam Levels and Water Supply Situation*. Retrieved from http://www.wuc.bw/wuc-content.php?cid=109

Zander, F. & Kralisch, S. (2016) River basin information system: Open environmental data management for research and decision making. *ISPRS International Journal of Geo-Information,* **5**, 123.

Zhang, L., & Mitsch, W.J. (2005) Modelling hydrological processes in created freshwater wetlands: An integrated system approach. *Environmental Modelling Software*, **20**, 935–946.

Zhao, T., & Dai, A. (2015) The magnitude and causes of global drought changes in the twenty-first century under a low–moderate emissions scenario. *Journal of Climatology*, **28**, 4490-4512.

Zimba, H., Kawawa, B., Chabala, A., Phiri, W., Selsam, P., Meinhardt, M. & Nyambe, I. (2018) Assessment of trends in inundation extent in the Barotse Floodplain, upper Zambezi River Basin: A remote sensing-based approach. *Journal of Hydrology: Regional Studies*, **15**, 149–170.

References [CrossRef]

Adams, W. M., Goudie, A. S. & Orme, A. R. (Eds.) (1999) *The Physical Geography of Africa*. Oxford Regional Environments, Oxford.

Adams, J.M., Gasparini, N.M., Hobley, D.E.J., Tucker, G.E., Hutton, E.W.H., Nudurupati, S.S., & Istanbulluoglu, E. (2016) The Landlab Overland Flow component: A Python library for computing shallow-water flow across watersheds. *Geoscience Model Development Discussions*, 1–34.

Ahmed, S., Dechmi, F. & Javier, B. (2011) Application of SWAT model to a sprinkler-irrigated watershed in the middle Ebro River Basin (Spain). The 2011 International Soil and Water Assessment Tool Conference, Toledo, Spain, 135–150.

Allgemeine Zeitung. (2016) Swakoppforte-Damm wird zur grünen Pfütze – Wasser für Karibib und Navachab. Retrieved from http://www.az.com.na/nachrichten/swakoppforte-damm-wird-zur-grnen-pftze-wasser-fr-karibib-und-navachab/

Andersson, L., Wilk, J., Todd, M.C., Hughes, D.A., Earle, A., Kniveton, D., Layberry, R., & Savenije, H.H.G. (2006) Impact of climate change and development scenarios on flow patterns in the Okavango River. Journal of Hydrology, **331**, 43–57. CrossRef

Archer, E., Conrad , J., Munch, Z., Opperman, D., Tadross, M., & Venter, J. (2009) Climate change, groundwater, and intensive commercial farming in the semi-arid northern Sandveld, South Africa. *Journal of Integrative Environmental Sciences*, **6**, 139–155. CrossRef

Arnold, J., Srinivasan, R., Muttiah, R. & Williams, J. (1998) Large-area hydrologic modelling and assessment. Part I, Model development. *Journal of the American Water Resources Association*, **34**, 73–89. CrossRef

Arnold, J. G. & Fohrer, N. (2005) SWAT2000: Current capabilities and research opportunities in applied watershed modelling. Hydrological Processes, **19**, 563–572. CrossRef

Baccari, N., Boussema, M. R., Lamachère, J-M. & Nasri, S. (2008) Efficiency of contour benches, filling-in and silting-up of a hillside reservoir in a semi-arid climate in Tunisia. *Comptes Rendus Geoscience*, **340**, 38–48. CrossRef

Baig, M.H.A., Wang, S., Zhang, L., Jiang, G., Lu, S., & Tong, Q. (2013) Comparison of MNDWI and DFI for water mapping in flooding season. Geoscience and Remote Sensing Symposium (IGARSS), 2013 IEEE International, 21–26 July 2013, pp. 2876–2879. CrossRef

Bastiaansen, C.J.M. (1995) Lui River Valley Model and some of its applications. *Rapport 55*, Landbouwuniversiteit Wageningen, Wageningen.

Beven, K. (2002) Runoff generation in semi-arid areas. *Dryland Rivers. Hydrology and Geomorphology of Semi-Arid Channels* (ed. by L. J. Bull & M. J. Kirkby.), 388. Wiley, Chichester, UK.

Branger, F., Gouttevin, I., Tilmant, F., Cipriani, T., Barachet, C., Montginoul, M., Le Gros, C., Sauquet, E., Braud, I. & Leblois, E. (2016) Distributed hydrological modelling of the Rhône river basin. http://cemadoc.irstea.fr/cemoa/PUB0005155

Conrad, J. & Munch, Z. (2006) Groundwater reserve determination required for the Sandveld, Olifants-Doorn water management area, GEOSS report no. 2005/04-20.

Druid, S. (2017) Uncertainties associated with hydrological terrain analysis in flat topography wetlands. Department of Earth Sciences, Uppsala University: Bachelor thesis.

DWA (Department of Water Affairs) (1992) A study of the impact of small dam construction on downstream water resources. *Final Report (No. 1).* DWA, Gaborone, Botswana.

DWA (Department of Water Affairs) (2006) *National Water Master Plan Review (SMEC/EHES) - Volume 3: Surface Water Resources*. DWA, Gaborone, Botswana

DWA (Department of Water Affairs) (2014a) A study of the impact of small dam construction on downstream water resources (updated). *Final Report (Draft).* DWA, Gaborone, Botswana.

DWA (Department of Water Affairs) (2014b) List of Registered Dams Jan. 2014. Government of South Africa, Capetown. Retrieved from https://www.dwa.gov.za/DSO/Documents/List%20of%20Registered%20Dams%20Jan%202014.xls

Engelbrecht, F., Adegoke, J., Bopape, M.J., Naidoo, M., Garland, R., Thatcher, M., McGregor, J., Katzfey, J., Werner, M., Ichoku, C., & Gatebe, C. (2015) Projections of rapidly rising surface temperatures over Africa under low mitigation. *Environmental Research Letters*, **10**, 1-16. CrossRef

Fernández, A., Najafi, M.R., Durand, M., Mark, B.G., Moritz, M., Jung, H.C., Neal, J., Shastry, A., Laborde, S., Phang, S.C., Hamilton, I.M., & Xiao, N. (2016) Testing the skill of numerical hydraulic modeling to simulate spatiotemporal flooding patterns in the Logone floodplain, Cameroon. *Journal of Hydrology*, **539**, 265–280. CrossRef

Flügel, W.-A. (1995) River salinisation due to dryland agriculture in the Western Cape Province, Republic of South Africa. *Environment International*, **21**, 679–686. CrossRef

FAO Subregional Office for Southern and East Africa (2004) Drought impact mitigation and prevention in the Limpopo River Basin: A situation analysis (No. 4). *Land and Water Discussion Paper*, **160**. Food and Agriculture Organization of the United Nations, Rome.

Foley, J.P. (2008) Centre pivot and lateral move machines. *WATERpak A Guide for Irrigation Management in Cotton*, pp. 195–220. Cotton Research and Development Corporation, Narrabri, Australia,

Fotso-Nguemo, T.C., Vondou, D.A., Pokam, W.M., Djomou, Z.Y., Diallo, I., Haensler, A., Tchotchou, L.A.D., Kamsu-Tamo, P.H., Gaye, A.T. & Tchawoua, C. (2017a) On the added value of the regional climate model REMO in the assessment of climate change signal over Central Africa. *Climate Dynamics*, **49,** 1-26. CrossRef

Fotso-Nguemo, T.C., Vondou, D.A., Tchawoua, C. & Haensler, A. (2017b) Assessment of simulated rainfall and temperature from the regional climate model REMO and future changes over Central Africa. *Climate Dynamics*, **48**, 3685–3705.

Fowler, H.J. & Kilsby, C.G. (2007) Using regional climate model data to simulate historical and future river flows in northwest England. *Climate Change*, **80**, 337–367. CrossRef

Franke, L., Steyn, M., & Haverkort, A. (2014) Series: Potato production in a changing climate II. What are the prospects for the Sandveld? *Technical News*, CHIPS.

Gaughan, A.E., Waylen, P.R. (2012) Spatial and temporal precipitation variability in the Okavango-Kwando-Zambezi catchment, southern Africa. *Journal of Arid Environments*, **82**, 19–30. CrossRef

Gerrits, A.M.J. (2005) Hydrological modelling of the Zambezi catchment from gravity measurements. Delft University of Technology, Delft; master's thesis.

Graf, W. L. (1988) *Fluvial Processes in Dryland Rivers*. Springer, New York. CrossRef

Gudmundsson, L., Bremnes, J.B., Haugen, J.E. & Engen-Skaugen, T. (2012) Technical Note: Downscaling RCM precipitation to the station scale using statistical transformations: A comparison of methods. *Hydrological Earth Systems Science*, **16**, 3383–3390. CrossRef

Güntner, A. (2002) Large-scale hydrological modelling in the semi-arid northeast of Brazil. University of Potsdam, Potsdam, Germany; dissertation.

Gupta, S.K. (2010) *Modern Hydrology and Sustainable Water Development*. Wiley-Blackwell, Oxford. CrossRef

Habets, F., Philippe, E., Martin, E., David, C. H. & Leseur, F. (2014) Small farm dams: Impact on river flows and sustainability in a context of climate change. *Hydrological Earth Systems Science*, **18**, 4207–4222. CrossRef

Hänsler, A., Hagemann, S. & Jacob, D. (2011) Dynamical downscaling of ERA40 reanalysis data over southern Africa: Added value in the simulation of the seasonal rainfall characteristics. International Journal of Climatology, **31**, 2338–2349. CrossRef

Hagi-Bischow, M. & Bonell, R.B. (2000) Assessment of LEACHM-C Model for semi-arid saline irrigation. *ICID Journal*, **49**, 29–42.

Hublart, P., Ruelland, D., Garc la De Cortázar Atauri, I. & Ibacache, A. (2015) Reliability of a conceptual hydrological model in a semi-arid Andean catchment facing water-use changes. *Proceedings of the IAHS*, **371**, 203–209. CrossRef

Hughes, D. A. (1995) Monthly rainfall-runoff models applied to arid and semiarid catchments for water resource estimation purposes. *Hydrological Sciences Journal*, **40**, 751–769. CrossRef

Hughes, D. A. (2004) Three decades of hydrological modelling research in South Africa. *South African Journal of Science*, **100**, 638–642. CrossRef

Hughes, D. A. & Mantel, S. K. (2010) Estimating the uncertainty in simulating the impacts of small farm dams on streamflow regimes in South Africa. *Hydrological Sciences Journal*, **55**, 578–592.

Hughes, D. A. (2007) Modelling semi-arid and arid hydrology and water resources: The southern Africa experience. *Hydrological Modelling in Arid and Semi-Arid Areas, International Hydrology Series* (ed. by H. Wheater , S. Sorooshian & K. D. Sharma), pp. 22-40. Cambridge University Press, Cambridge.

Hunter, N.M., Bates, P.D., Horritt, M.S., & Wilson, M.D. (2007) Simple spatially distributed models for predicting flood inundation: A review. *Geomorphology*, **90**, 208–225. CrossRef

IGC (International Growth Centre). (2016) Lights out: Zambia's electricity crisis. Retrieved from http://www.theigc.org/blog/lights-out-zambias-electricity-crisis/

Jung, H. & Jasinski, M.F. (2015) Sensitivity of a floodplain hydrodynamic model to satellite-based DEM scale and accuracy: Case study, the Atchafalaya Basin. *Remote Sensing*, **7**, 7938–7958. CrossRef

Kingumbi, A., Besbes, M., Bourges, J. & Garetta, P. (2004) Evaluation des transferts entre barrage et aquifères par la méthode de bilan d'une retenue en zone semi-aride. Cas d'El Haouareb en Tunisie centrale. *Revue des sciences de l´eau*, **17**, 213–225. CrossRef

Kling, H., Stanzel, P., & Preishuber, M. (2014) Impact modelling of water resources development and climate scenarios on Zambezi River discharge. *Journal of Hydrology: Regional Studies*, **1**, 17–43. CrossRef

Knight, D.J. (1990) The proven usefulness of instrumentation systems on varied dam projects. *Geotechnical Instrumentation in Practice: Purpose, Performance and Interpretation: Proceedings of the Conference on Geotechnical Instrumentation in Civil Engineering Projects*, pp. 401–414. Thomas Telford, London.

Knight, F.H., Conrad, J. & Helme, N. (2007) *Biodiversity Best Practise Guidelines for Potato Production in the Sandveld*. Potatoes South Africa, Pretoria.

Knoche, M., Fischer, C., Pohl, E., Krause, P. & Merz, R. (2014) Combined uncertainty of hydrological model complexity and satellite-based forcing data evaluated in two data-scarce semi-arid catchments in Ethiopia. *Journal of Hydrology*, **519**, 2049–2066. CrossRef

Kralisch, S. & Krause, P. (2006) JAMS: A framework for natural resource model development and application. *Proceedings of the iEMSs Third Biannual Meeting, 'Summit on Environmental Modelling and Software'* (ed. by A. Voinov, A. Jakeman & A. Rizzoli.). Burlington, Vermont, USA. Retrieved from http://www.iemss.org/iemss2006/papers/s5/254_Kralisch_1-4.pdf

Krause, P. (2001) Das Hydrologische Modellsystem J2000. Beschreibung und Anwendung in großen Flussgebieten. *Reihe Umwelt*, Vol. 29. Schriften des Forschungszentrum Jülich.

Krause, P. (2002) Quantifying the impact of land use changes on the water balance of large catchments using the J2000 model. *Physics and Chemistry of the Earth, Parts ABC*, **27**, 663–673. CrossRef

Krause, P., Bäse, F., Bende-Michl, U., Fink, M., Flügel, W. & Pfennig, B. (2006) Multiscale investigations in a mesoscale catchment: Hydrological modelling in the Gera catchment. *Advances in Geosciences*, **9**, 53–61. CrossRef

Krause, P., Boyle, D.P. & Bäse, F. (2005) Comparison of different efficiency criteria for hydrological model assessment. *Advances in Geosciences*, **5**, 89–97. CrossRef

Kusangaya, S., Warburton, M.L., Archer van Garderen, E., & Jewitt, G.P.W. (2014) Impacts of climate change on water resources in southern Africa: A review. *Physics and Chemistry of the Earth*, **67–69**, 47–54. CrossRef

Lesschen, J. P., Schoorl, J. M. & Cammeraat, L. H. (2009) Modelling runoff and erosion for a semi-arid catchment using a multiscale approach based on hydrological connectivity. *Geomorphology*, **109**, 174–183. CrossRef

Mantel, S. K., Muller, N. W. & Hughes, D. A. (2010) Ecological impacts of small dams on South African rivers Part 2: Biotic response: Abundance and composition of macroinvertebrate communities. *Water SA*, **36**, 361–370.

Mason, S.J. & Jury, M.R. (1997) Climatic variability and change over southern Africa: A reflection on underlying processes. *Progress in Physical Geography*, **21**, 23-50. CrossRef

Mathee, J. A. La G. (1984) Beskerming van Bewerkte Landerye. *National Soil Conservation Manual*. (Directorate of Agricultural Engineering and Water Supply), chapter 8. Goverment Printer, Pretoria, South Africa.

Mazvimavi, D. & Wolski, P. (2006) Long-term variations of annual flows of the Okavango and Zambezi Rivers. *Physics and Chemistry of the Earth*, **31/15**, 944-951. CrossRef

McCartney, M., Cai, X., Smakhtin, V. (2013) Evaluating the flow regulating functions of natural ecosystems in the Zambezi River Basin. *IWMI Research Report 148*. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Meigh, J. (1995) The impact of small farm reservoirs on urban water supplies in Botswana. *Natural Resource Forum*, **19**, 71–83. CrossRef

Meinhardt, M. (2017) Auswirkungen des Klimawandels auf die Hydrologie im Oberen Zambezi: Ein prozessbasierter räumlich distributiver Modellierungsansatz zur Quantifizierung der hydrologischen Veränderungen unter Berücksichtigung der jährlichen Überflutung. FSU Jena: Dissertation. Retrieved from http://nbn-resolving.de/urn:nbn:de:gbv:27-dbt-20170616-1130019

Miller, J.A., Watson, A.P., Fleischer, M., Eilers, A., Sigidi, N.T., van Gend, J., van Royen, J., Butler, M., Clarke, C.E. & de Clercq, W. (2018) Groundwater quality, quantity, and recharge estimation on the west coast of South Africa. This volume. CrossRef

Miola, A. & Simonet, C. (2014) *Concepts and Metrics for Climate Change Risk and Development: Towards an Index for Climate Resilient Development*. Joint Research Centre, Science and Policy Reports. Publications Office of the European Union, Luxembourg.

Mitsch, W.J. & Gosselink, J.G. (2000) *Wetlands*. John Wiley & Sons, New York.

MMEGI (2016) Gaborone Dam springs to life. Retrieved from http://www.mmegi.bw/index.php?aid=58643&dir=2016/march/17

Nasri, S. (2007) Caractéristiques et impacts hydrologiques de banquettes en cascade sur un versant semi-aride en Tunisie central. *Hydrological Science Journal*, **52**, 1134–1145. CrossRef

Nciizah, A.D. & Wakindiki, I.C. (2015) Soil sealing and crusting effects on infiltration rate: a critical review of shortfalls in prediction models and solutions. *Archives of Agronomy and Soil Science*, **61**, 1211–1230. CrossRef

Nel, J.M. (2004) Assessment of the groundwater potential of the Langvlei catchment with special emphasis on the protection of the water resources and management options, report no. GH-4000. Department of Water Affairs and Forestry, Pretoria, South Africa.

Nepal, S. (2002) *Evaluating Upstream-Downstream Linkages of Hydrological Dynamics in the Himalayan Region.* Friedrich Schiller University, Jena.

New York Times. (2016) Climate change hits hard in Zambia, an African success story. Retrieved from http://www.nytimes.com/2016/04/13/world/africa/zambia-drought-climate-change-economy.html?_r=0

Omary, M., Camp, C.R. & Sadler, E.J. (1997) Centre pivot irrigation system modification to provide variable water application depths. *Transactions of the ASAE*, **13**, 235–239.

Ouessar, M., Bruggeman, A., Abdelli, F., Mohtar, R.H., Gabriels, D. & Cornelis, W.M. (2009) Modelling water-harvesting systems in the arid south of Tunisia using SWAT. *Hydrology and Earth System Sciences*, **13**, 2003–2021. CrossRef

Pan, F., Stieglitz, M. & McKane, R. B. (2012) An algorithm for treating flat areas and depressions in digital elevation models using linear interpolation. *Water Resources Research*, **48**. CrossRef

Parida, B. P., Moalafhi, D. B. & Kenabatho, P. K. (2006) Forecasting runoff coefficients using ANN for water resources management: The case of Notwane catchment in Eastern Botswana. *Physics and Chemistry of the Earth*, **31**, 928–934. CrossRef

Peel, M. C., Finlayson, B. L. & MacMahon, T. A. (2007) Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth Science Systems Discussion*, **4**, 439–473. CrossRef

Pfennig, B., Kipka, H., Wolf, M., Fink, M., Krause, P. & Flügel, W. A. (2009) Development of an extended routing scheme in reference to consideration of multi-dimensional flow relations between hydrological model entities, 1972–1978. Presented at the 18th World IMACS / MODSIM Congress, Cairns, Australia. Retrieved from http://mssanz.org.au/modsim09

Pilgrim, D. H., Chapman, T. G. & Doran, D. G. (1988) Problems of rainfall-runoff modelling in arid and semi-arid regions. *Hydrological Sciences Journal*, **33**, 379–400. CrossRef

Plessis, A. J. E. D. & Rowntree, K. M. (2003) Water resources in Botswana with particular reference to the savanna regions. *South African Geography Journal*, **85**, 42–49. CrossRef

Potatoes South Africa. (2015) *2014/2015 Potato Industry Report*. Potatoes South Africa, Pretoria.

Pramanik, N., Panda, R.K., & Sen, D. (2010) One-dimensional hydrodynamic modeling of river flow using DEM extracted river cross-sections. *Water Resources Management*, **24**, 835–852. CrossRef

Schulze, R.E. (2000) Modelling hydrological responses to land use and climate change: A southern African perspective. *AMBIO: A Journal of the Human Environment*, **29**, 12. CrossRef

Schwartze, C., Kralisch, S. & Flügel, W.-A. (2012) Virtual appliances for geospatial data processing. *Proceedings of the International Congress on Environmental Modelling and Software, Sixth Biennial Meeting* (ed. by R. Seppelt, A. A. Voinov, S. Lange & D. Bankamp). Leipzig, Germany. Retrieved from http://www.iemss.org/iemss2012/proceedings/G1_2_0914_Schwartze_et_al.pdf

Schwartze, C. (2008) Deriving Hydrological Response Units (HRUs) using a web processing service implementation based on GRASS GIS. *Proceedings of the Workshop Geoinformatics FCE CTU 2008*, **3**, 67–78. Presented at the Geoinformatics FCE CTU 2008 Workshop, Technical University, Prague, Czech.

Smith, R.E. & Goodrich, D.C. (2005) Rainfall excess overland flow. *Encyclopedia of Hydrological Sciences* (ed. by M. G. Anderson & J. J. McDonnell), pp. 1707–1718. Wiley & Sons, Chichester, UK.

SREX. (2012) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* (ed. by C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, & P.M. Midgley). Cambridge University Press, Cambridge, UK, and New York, NY, USA.

Steudel, T., Bugan, R., Kipka, H., Pfennig, B., Fink, M., de Clercq, W., Flügel, W.-A. & Helmschrot, J. (2015) Implementing contour bank farming practices into the J2000 model to improve hydrological and erosion modelling in semi-arid Western Cape Province of South Africa. *Hydrology Research*, **46**, 192. CrossRef

Steudel, T., Göhmann, H., Flügel, W.-A. & Helmschrot, J. (2013a) Hydrological assessment of hydrological dynamics in the upper Okavango. *Biodiversity & Ecology*, **5**, 247-261. CrossRef

Steudel, T., Göhmann, H., Mosimanyana, E., Quintino, M., Flügel, W.-A. & Helmschrot, J. (2013b) Okavango Basin - Hydrology. *Biodiversity & Ecology*, **5**, 19-22. CrossRef

Thompson, J.R., Sorenson, H.R., Gavin, H., & Refsgaard, A. (2004) Application of the coupled MIKE SHE/MIKE 11 modelling system to a lowland wet grassland in southeast England. Journal of Hydrology, **293**, 151–179. CrossRef

Tighe, M.L. & Chamberlain, D. (2009) Accuracy comparison of the SRTM, ASTER, NED, Nextmap® USA digital terrain model over several USA study sites. ASPRS/MAPPS 2009 Fall Conference, November 16-19.

Todd, M.C., Andersson, L., Hughes, D.A., Kniveton, D., Layberry, R., Murray-Hudson, M., Savenije, H.H.G., Wilk, J., & Wolski, P. (2008) Simulating climate impacts on water resources: Experience from the Okavango River, southern Africa. *Hydrological Modelling and the Water Cycle: Coupling the Atmospheric and Hydrological Models*, pp. 243-265. Springer, Heidelberg.

van Wilgen, N.J., Goodall, V., Holness, S., Chown, S.L. & McGeoch, M.A. (2016) Rising temperatures and changing rainfall patterns in South Africa's national parks. *International Journal of Climatology*, **36**, 706–721. CrossRef

ver West, J. (2002) *Hydrologic Analysis in Flat Terrain*. Texas A&M University, Department of Civil Engineering.

Wakindiki, I. I. C., Mochoge, B. O. & Semoka, J. M. R. (2007) Assessment of indigenous soil and water conservation technology for smallholder farms in semi-arid areas in Africa and close spaced trash lines effect of erosion and crop yield. *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities* (ed. by A. Bationo, B. Waswa, J. Kihara & J. Kimetu), pp. 805–814. Springer, Dordrecht.

Wang, S., Baig, M. A., Zhang, G., Jiang, L.S., & Tong, Q. (2013) Comparison of MNDWI and DFI for water mapping in flooding season. *Chinese Academy of Sciences*, 2876–2879.

Watson, A., Miller, J., Fleischer, M. & de Clercq, W. (2018) Estimation of groundwater recharge via percolation outputs from a rainfall/runoff model for the Verlorenvlei estuarine system, west coast, South Africa. *Journal of Hydrology*, **558**, 238–254. CrossRef

Wheater, H. S. (2008) Modelling hydrological processes in arid and semi-arid areas: An introduction to the workshop. *Hydrological Modeling in Arid and Semi-Arid Areas* (ed. by H.S. Wheater, S. Sorooshian & K.D. Sharma), 1–22. Cambridge University Press, New York.

Winsemius, H.C., Savenije, H.H.G., Gerrits, a. M.J., Zapreeva, E. a., Klees, R. (2006) Comparison of two model approaches in the Zambezi River basin with regard to model reliability and identifiability. *Hydrological Earth Systems Science Discussions*, **2**, 2625–2661. CrossRef

Wolf, M., Pfennig, B., Krause, P. & Flügel, W.-A. (2009) Delineation of topographic process entities using SRTM for hydrological modelling. *18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation* (ed. by R.S. Anderssen, R.D. Braddock & L.T.H. Newham), pp. 2021–2027. Modelling and Simulation Society of Australia and New

Zealand and International Association for Mathematics and Computers in Simulation.
Wolski, P., Todd, M.C., Murray-Hudson, M.A., & Tadross, M. (2012) Multi-decadal oscillations in the hydro-climate of the Okavango River system during the past and under a changing climate. *Journal of Hydrology*, **475**, 294–305. CrossRef
WUC. (2014) *Dam Levels and Water Supply Situation*. Retrieved from http://www.wuc.bw/wuc-content.php?cid=109
Zander, F. & Kralisch, S. (2016) River basin information system: Open environmental data management for research and decision making. *ISPRS International Journal of Geo-Information,* **5**, 123. CrossRef
Zhang, L., & Mitsch, W.J. (2005) Modelling hydrological processes in created freshwater wetlands: An integrated system approach. *Environmental Modelling Software*, **20**, 935–946. CrossRef
Zhao, T., & Dai, A. (2015) The magnitude and causes of global drought changes in the twenty-first century under a low–moderate emissions scenario. *Journal of Climatology*, **28**, 4490-4512. CrossRef
Zimba, H., Kawawa, B., Chabala, A., Phiri, W., Selsam, P., Meinhardt, M. & Nyambe, I. (2018) Assessment of trends in inundation extent in the Barotse Floodplain, upper Zambezi River Basin: A remote sensing-based approach. *Journal of Hydrology: Regional Studies*, **15**, 149–170. CrossRef

Risk management

Risk management – a conceptual foundation

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Abstract: Risk is the potential interplay of a natural hazard, exposed elements in the respective area, and the vulnerability of these elements. We provide a general conceptualisation of risk against the background of globally increasing hazard events and, at the same time, increasing numbers of exposed and vulnerable elements resulting from population and economic growth as well as environmental degradation and exploitation of resources. We discuss general strategies for risk management and provide an overview of the situation in southern Africa, based on the field studies described in this chapter.

Resumo: Risco é a potencial interacção entre um perigo natural, elementos expostos na área respectiva e a vulnerabilidade desses elementos. A conceptualização geral de risco é dada em relação ao contexto do crescimento global de eventos de perigo e, ao mesmo tempo, ao aumento do número de elementos expostos e vulneráveis devido ao crescimento populacional e económico, bem como à degradação ambiental e exploração de recursos. Discutimos estratégias gerais para a gestão de riscos e fornecemos uma visão especial sobre a situação na África Austral, com base nos estudos de campo deste capítulo.

Introduction

In recent decades, the number of reported natural hazards such as earthquakes, tsunamis, storms, droughts, or floods has increased significantly. While most geophysical events (e.g. earthquakes), which are beyond the influence of humankind, remain generally constant with respect to intensity and occurrence over time, meteorological, hydrological, and climatological events pushed the annual total from about 200 in 1980 to almost 800 in 2016 (Munich Re, 2017). A prominent recent example is typhoon Haiyan hitting the Philippines, Vietnam, and China in 2013 and causing damage to 1.1 million houses and the evacuation and displacement of more than 4.5 million people. More than 6,200 people died in this disaster and the economic loss is estimated to have been US$ 10,500 M (Munich Re, 2014). At US$ 20,000 M, the economic loss caused by floods in China in 2016 was even greater. However, this was soon to be topped by the costliest tropical cyclone on record to date: Hurricane Harvey hitting the U.S. coast in 2017 and inflicting damage amounting to US$ 125,000 M. Due to heavy seasonal rains in this episode, rivers burst their banks and affected more than 60 million people (Munich Re, 2017). Further hydrological events, such as severe floods in India in 2015 and a recently occurring landslide in China in 2017, contribute to the increasing number of reported natural hazards. In the African context, particular attention is given to drought events, which affect vulnerable populations and frequently result in severe famines. Since 1900, 291 drought events have occurred on this continent with almost 850,000 people killed and up to US$ 3,000 M of economic damage (Masih et al., 2014). The most recent examples of droughts were aggravated by El Nino, leading to the humanitarian crisis in the Horn of Africa (FEWS-NET, 2017) and persisting water shortages in southern Africa (Archer et al., 2017).

In general, natural hazards such as floods, droughts, storms, and tropical cyclones, among many others, are potentially damaging physical events, phenomena, or human activities that are characterised by their location, intensity, frequency and probability (UN/ISDR, 2004).

However, natural hazards do not intrinsically cause harm to people, assets, and societies. Risks are only created when there is spatial and temporal coincidence of natural hazards in areas of exposed and vulnerable elements, such as individuals, households, communities, buildings, infrastructure, as well as agricultural commodities, and environmental assets. *Exposure* can generally be considered as the location and characteristics of the 'elements at risk'. *Vulnerability* is defined as "the conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of a hazard" (UN/ISDR, 2004). The consequential *risks* and related potential disasters can be viewed as an interplay of complex reciprocity between potentially damaging physical events (in our case the focus is on water-related hazards such droughts and floods) and the vulnerability of the built and natural environment, society, and economy (Birkmann, 2006; Geiß & Taubenböck, 2013).

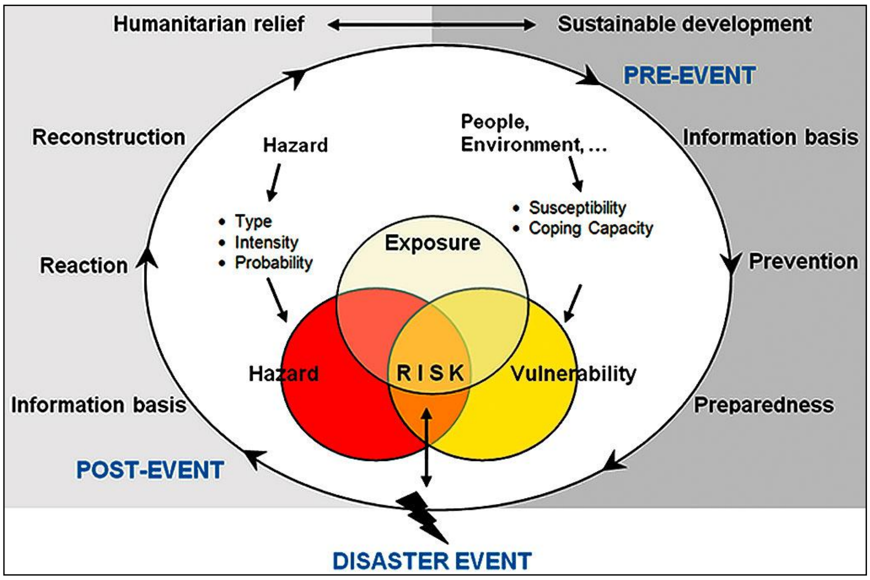

Figure 1: Risk as a result of the interaction of the hazard and the vulnerability embedded in the various phases of the disaster management cycle (adapted from Wisner, 2004; Taubenböck et al., 2008).

Conceptual foundation: hazards, exposure, vulnerabilities and risks

The concept of risk itself is subject to a vibrant debate within the scientific community. In recent years, a shift from hazard-oriented research strategies towards more integrative approaches to assessing risk and its components, incorporating also human, societal, and cultural factors, can be observed (Pelling, 2003; Taubenböck et al., 2008). This change can be related to the realisation that natural hazards do not have an intrinsic dangerous character themselves, but become disastrous if several unfavourable parameters come together. This relationship can be expressed as:

Risk = *f*(Hazard, Exposure, Vulnerability). (eq1)

Here, risks are seen as a function of the future interplay of specific hazards, exposed elements and their vulnerabilities. The '*hazard*' component in equation 1 is defined as the probability of a disastrous event happening in a certain period of time, with a particular intensity at a particular location (UNESCO, 1973). The second component, '*exposure*', is defined as the degree, duration, and/or extent to which a system is in contact with, or subject to, perturbation (Kasperson et al., 2005; Adger, 2006). The third component, '*vulnerability*', is the relationship between the system's exposure and susceptibility to a stressor with the coping capacity of the system, that is, its potential to mitigate the impact of the hazard (UN/ISDR, 2004; Birkmann, 2006).

While risks imply a potentially damaging future event, the disaster management cycle puts the conceptual idea of risk into the full cycle of the timeline (see Fig. 1): The disaster management cycle contains pre-event preparedness and disaster reaction (or response) and provides insight of the conceptual idea at different stages (Fig. 1).

The management of risks: early warning and mitigation strategies

The management of risks – independent of the time before, during, or after an event – relies on the availability of up-to-date and appropriate information (in terms of thematic, temporal, and geometric resolution). Based on these data, the assessment of hazards, exposure, vulnerability, and ultimately risks, can be conducted as a basis for formulating and implementing early-warning systems and mitigation/prevention strategies, as well as pre-event preparedness plans. Technological solutions in combination with community-centred strategies have been reported to be successful in this regard (e.g. Kelbessa, 2009; Taubenböck et al., 2009).

In addition, this kind of knowledge base is also crucial in the post-event phase. It is necessary for informing reactions (response) in terms of humanitarian relief or reconstruction strategies. For example, rapid mapping mechanisms such as from the International Charter "Space and Major Disasters", the Emergency Management Service of the European COPERNICUS program, the United Nations (UNOSAT-UNITAR), and SENTINEL ASIA, have been developed for providing fast, standardised spatial information products (Voigt et al., 2016).

However, the application of scientific findings to the mitigation of impacts holds many challenges, from issues of unclear communication and stakeholders with different interests, to stakeholders not being aware of available information (see examples of these challenges in Taubenböck et al., 2013).

The situation in southern Africa

In large parts of Africa, drought is often the most frequent climate-related disaster with devastating effects on water supply, crop production, and rearing of livestock (Masih et al., 2014; Spinoni et al., 2014). In the following chapter, drought will be examined from natural and social science perspectives. On the one hand, Müller et al. (2018) describe methods to undertake long-term analyses of droughts based on remote sensing data. In a case study, they compare the proportion of land cover classes affected by droughts of different persistency in South Africa and Botswana in 2015/2016. On the other hand, Luetkemeier & Liehr (2018) provide insights into drought sensitivity in the Cuvelai Basin of northern Namibia and southern Angola. As part of a social-ecological drought risk analysis (Luetkemeier & Liehr, under review), they empirically assess local water and food consumption patterns to identify critical water dependence structures at the household level. In combination with a recent drought hazard assessment (Luetkemeier et al., 2017), this study provides stakeholders with a comprehensive information base for drought impact mitigation.

Besides the hazard of drought, the subsequent articles discuss the hazard of intensified exploitation of natural resources, which imposes negative effects on vital ecosystems and environments in Africa. In this regard, Olivier et al. (2018) investigate sediment movement in discontinuous gully systems in the Swartland region in the Western Cape of South Africa. They confirm that the gully systems are no relics of the past, but rather, active erosive systems that destroy fertile soils and hence undermine long-term sustainability of the farming systems. Interestingly, they find that conservation techniques such as contour ploughing can even aggravate the problem. Ferreira-Baptista et al. (2018) examine the pollution effects of mining activities on water resources in north-eastern Angola. They observe multiple negative effects on water bodies from deforestation, soil depletion, and topographic changes in nearly all of the north-eastern provinces of Angola.

Outlook

The observed climatologically-driven increase of natural hazards exposes an ever-increasing amount of area and number of people around the globe to risks. A consequence of these changing environments and related living conditions is forced migration into cities within and across borders (Davis, 2007). This leads to an additional concern: the clustering of exposed elements at risk in ever-expanding urban areas (Taubenböck et al., 2012).

These processes of global change (climate change, urbanisation, etc.) demand constant vigilance, which requires the availability of environmental and socio-economic monitoring data. Besides in-situ information, understanding the spatial inter-relationship of these processes demands geospatial (primarily remote sensing) data and methods. These have become crucial tools for monitoring and integrating information on natural and societal processes and provide decision-makers with targeted knowledge to perform adapted disaster risk mitigation tasks.

Beyond the technical aspects, which are exemplified in the following chapters of this book, one of the main challenges in the field of disaster risk reduction is to change people's perceptions so that they recognise disasters as the outcome of a process in which societies have implicitly generated vulnerabilities and risks (Villagrán de León, 2006). Or, as Rashed & Weeks (2003) put it: assessing risks and managing disastrous events is an ill-structured problem (i.e. a problem for which there is no unique, identifiable, objectively optimal solution). However, new conceptual perspectives combined with latest data and technical solutions allow a more comprehensive understanding of these complex processes.

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References

Adger, W.N. (2006) Vulnerability. *Global environmental change*, **16**, 268–281.

Archer, E.R.M., Landman, W.A., Tadross, M.A., Malherbe, J., Weepener, H., Maluleke, P. & Marumbwa, F.M. (2017) Understanding the evolution of the 2014–2016 summer rainfall seasons in southern Africa: Key lessons. *Climate Risk Management*, **16**, 22–28.

Birkmann, J. (Ed.). (2006) *Measuring vulnerability to natural hazards: towards disaster resilient societies*, United Nations University, Tokyo, New York.

Davis, M. (2007) *Planet of slums*, Verso, London.

Ferreira-Baptista, L., Aguiar, P.F., Pereira, M.J. & Manuel, J. (2018) Impact of mining on the environment and water resources in north-eastern Angola. This volume.

FEWS-NET (2017) *East Africa special report. Illustrating the extent and severity of the 2016/17 Horn of Africa drought*, Famine Early Warning System Network (FEWS-NET).

Geiß, C. & Taubenböck, H. (2013) Remote sensing contributing to assess earthquake risk: from a literature review towards a roadmap. *Natural Hazards*, **68**, 7–48.

Kasperson, R.E., Dow, K., Archer, E.R.M., Cáceres, D., Downing, T.E., Elmqvist, T., Eriksen, S., Folke, C., Han, G., Iyengar, K., Vogel, C., Wilson, K.A. & Ziervogel, G. (2005) *Vulnerable people and places. Ecosystems and human well-being: current state and trends* (ed. by R. Hassan, R. Scholes, and N. Ash), pp. 143–164. Island Press.

Kelbessa, W. (2009) *Meltdown: Climate change, natural disasters, and other catastrophes – fears and concerns of the future.* (ed. by K. Gow), pp. 247–267. Nova Science Publishers New York, NY.

Luetkemeier, R., Stein, L., Drees, L. & Liehr, S. (2017) Blended Drought Index: Integrated drought hazard assessment in the Cuvelai-Basin. *Climate*, **5**, 51.

Luetkemeier, R., Liehr, S., under review. Household Drought Risk Index (HDRI): Social-ecological assessment of drought risk in the Cuvelai-Basin. Journal of Natural Resources and Development (JNRD).

Luetkemeier, R. & Liehr, S. (2018) Drought sensitivity in the Cuvelai-Basin: Empirical analysis of seasonal water and food consumption patterns. This volume.

Masih, I., Maskey, S., Mussá, F.E.F. & Trambauer, P. (2014) A review of droughts on the African continent: a geospatial and long-term perspective. *Hydrology and Earth System Sciences*, **18**, 3635–3649.

Müller, I., Hippondoka, M., Winkler, K., Geßner, U., Martinis, S. & Taubenböck, H. (2018) Monitoring flood and drought events – eartch observation for multiscale assessment of water-related hazards and exposed elements. This volume.

Munich Re (2014) Natural catastrophes 2013. Analyses, assessments, positions. *Topics Geo*.

Munich Re (2017) Natural catastrophes 2016. Analyses, assessments, positions. *Topics Geo*.

Olivier, G., Helmschrot J. & de Clercq, W.P. (2018) Are large classical gully systems inactive remnants of the past – a field based case study investigating sediment movement. This volume.

Pelling, M. (2003) *The vulnerability of cities: natural disasters and social resilience*, Earthscan.

Rashed, T. & Weeks, J. (2003) Assessing vulnerability to earthquake hazards through spatial multicriteria analysis of urban areas. *International Journal of Geographical Information Science*, **17**, 547–576.

Spinoni, J., Naumann, G., Carrao, H., Barbosa, P. & Vogt, J. (2014) World drought frequency, duration, and severity for 1951-2010. *International Journal of Climatology*, **34**, 2792–2804

Taubenböck, H., Esch, T., Felbier, A., Wiesner, M., Roth, A. & Dech, S. (2012) Monitoring urbanization in mega cities from space. *Remote sensing of Environment*, **117**, 162–176.

Taubenböck, H., Goseberg, N., Lämmel, G., Setiadi, N., Schlurmann, T., Nagel, K., Siegert, F., Birkmann, J., Traub, K.-P., Dech, S., Keuck, V., Lehmann, F., Strunz, G. & Klüpfel, H. (2013) Risk reduction at the "Last-Mile": an attempt to turn science into action by the example of Padang, Indonesia. *Natural Hazards*, **65**, 915–945.

Taubenböck, H., Goseberg, N., Setiadi, N., Lämmel, G., Moder, F., Oczipka, M., Klüpfel, H., Wahl, R., Schlurmann, T., Strunz, G., Birkmann, J., Nagel, K., Siegert, F., Lehmann, F., Dech, S., Gress, A. & Klein, R. (2009) Last-

Mile” preparation for a potential disaster – Interdisciplinary approach towards tsunami early warning and an evacuation information system for the coastal city of Padang, Indonesia. *Natural Hazards and Earth System Science*, **9**, 1509–1528.
Taubenböck, H., Post, J., Roth, A., Zosseder, K., Strunz, G. & Dech, S. (2008) A conceptual vulnerability and risk framework as outline to identify capabilities of remote sensing. *Natural Hazards and Earth System Sciences*, **8**, 409–420.
UN/ISDR (2004) *Living with risk: A global review of disaster reduction initiatives*, United Nations publications, Geneva, Switzerland.
UNESCO (1973) *Annual Summary of Information on Natural Disasters*, UNESCO Press, Paris.
Villagrán de León, J.C. (2006) *Vulnerability: a conceptual and methodological review institute of environment and human security*, United Nations University - Institute for Environment and Human Security.
Voigt, S., Giulio-Tonolo, F., Lyons, et al. (2016) Global trends in satellite-based emergency mapping. *Science*, **353**, 247–252.
Wisner, B. (2004) *At risk: Natural hazards, people’s vulnerability and disasters*, Psychology Press, London.

References [CrossRef]

Adger, W.N. (2006) Vulnerability. *Global environmental change*, **16**, 268–281. CrossRef

Archer, E.R.M., Landman, W.A., Tadross, M.A., Malherbe, J., Weepener, H., Maluleke, P. & Marumbwa, F.M. (2017) Understanding the evolution of the 2014–2016 summer rainfall seasons in southern Africa: Key lessons. *Climate Risk Management*, **16**, 22–28. CrossRef

Birkmann, J. (Ed.). (2006) *Measuring vulnerability to natural hazards: towards disaster resilient societies*, United Nations University, Tokyo, New York.

Davis, M. (2007) *Planet of slums*, Verso, London.

Ferreira-Baptista, L., Aguiar, P.F., Pereira, M.J. & Manuel, J. (2018) Impact of mining on the environment and water resources in north-eastern Angola. This volume. CrossRef

FEWS-NET (2017) *East Africa special report. Illustrating the extent and severity of the 2016/17 Horn of Africa drought*, Famine Early Warning System Network (FEWS-NET).

Geiß, C. & Taubenböck, H. (2013) Remote sensing contributing to assess earthquake risk: from a literature review towards a roadmap. *Natural Hazards*, **68**, 7–48. CrossRef

Kasperson, R.E., Dow, K., Archer, E.R.M., Cáceres, D., Downing, T.E., Elmqvist, T., Eriksen, S., Folke, C., Han, G., Iyengar, K., Vogel, C., Wilson, K.A. & Ziervogel, G. (2005) *Vulnerable people and places. Ecosystems and human well-being: current state and trends* (ed. by R. Hassan, R. Scholes, and N. Ash), pp. 143–164. Island Press.

Kelbessa, W. (2009) *Meltdown: Climate change, natural disasters, and other catastrophes – fears and concerns of the future*. (ed. by K. Gow), pp. 247–267. Nova Science Publishers New York, NY.

Luetkemeier, R., Stein, L., Drees, L. & Liehr, S. (2017) Blended Drought Index: Integrated drought hazard assessment in the Cuvelai-Basin. *Climate*, **5**, 51. CrossRef

Luetkemeier, R., Liehr, S., under review. Household Drought Risk Index (HDRI): Social-ecological assessment of drought risk in the Cuvelai-Basin. Journal of Natural Resources and Development (JNRD).

Luetkemeier, R. & Liehr, S. (2018) Drought sensitivity in the Cuvelai-Basin: Empirical analysis of seasonal water and food consumption patterns. This volume. CrossRef

Masih, I., Maskey, S., Mussá, F.E.F. & Trambauer, P. (2014) A review of droughts on the African continent: a geospatial and long-term perspective. *Hydrology and Earth System Sciences*, **18**, 3635–3649. CrossRef

Müller, I., Hippondoka, M., Winkler, K., Geßner, U., Martinis, S. & Taubenböck, H. (2018) Monitoring flood and drought events – eartch observation for multiscale assessment of water-related hazards and exposed elements. This volume. CrossRef

Munich Re (2014) Natural catastrophes 2013. Analyses, assessments, positions. *Topics Geo*.

Munich Re (2017) Natural catastrophes 2016. Analyses, assessments, positions. *Topics Geo*.

Olivier, G., Helmschrot J. & de Clercq, W.P. (2018) Are large classical gully systems inactive remnants of the past – a field based case study investigating sediment movement. This volume. CrossRef

Pelling, M. (2003) *The vulnerability of cities: natural disasters and social resilience*, Earthscan.

Rashed, T. & Weeks, J. (2003) Assessing vulnerability to earthquake hazards through spatial multicriteria analysis of urban areas. *International Journal of Geographical Information Science*, **17**, 547–576. CrossRef

Spinoni, J., Naumann, G., Carrao, H., Barbosa, P. & Vogt, J. (2014) World drought frequency, duration, and severity for 1951-2010. *International Journal of Climatology*, **34**, 2792–2804. CrossRef

Taubenböck, H., Esch, T., Felbier, A., Wiesner, M., Roth, A. & Dech, S. (2012) Monitoring urbanization in mega cities from space. *Remote sensing of Environment*, **117**, 162–176. CrossRef

Taubenböck, H., Goseberg, N., Lämmel, G., Setiadi, N., Schlurmann, T., Nagel, K., Siegert, F., Birkmann, J., Traub, K.-P., Dech, S., Keuck, V., Lehmann, F., Strunz, G. & Klüpfel, H. (2013) Risk reduction at the “Last-Mile”: an attempt to turn science into action by the example of Padang, Indonesia. *Natural Hazards*, **65**, 915–945. CrossRef

Taubenböck, H., Goseberg, N., Setiadi, N., Lämmel, G., Moder, F., Oczipka, M., Klüpfel, H., Wahl, R., Schlurmann, T., Strunz, G., Birkmann, J., Nagel, K., Siegert, F., Lehmann, F., Dech, S., Gress, A. & Klein, R. (2009) Last-Mile" preparation for a potential disaster – Interdisciplinary approach towards tsunami early warning and an evacuation information system for the coastal city of Padang, Indonesia. *Natural Hazards and Earth System Science*, **9**, 1509–1528. CrossRef

Taubenböck, H., Post, J., Roth, A., Zosseder, K., Strunz, G. & Dech, S. (2008) A conceptual vulnerability and risk framework as outline to identify capabilities of remote sensing. *Natural Hazards and Earth System Sciences*, **8**, 409–420. CrossRef

UN/ISDR (2004) *Living with risk: A global review of disaster reduction initiatives*, United Nations publications, Geneva, Switzerland.

UNESCO (1973) *Annual Summary of Information on Natural Disasters*, UNESCO Press, Paris.

Villagrán de León, J.C. (2006) *Vulnerability: a conceptual and methodological review institute of environment and human security*, United Nations University - Institute for Environment and Human Security.

Voigt, S., Giulio-Tonolo, F., Lyons, et al. (2016) Global trends in satellite-based emergency mapping. *Science*, **353**, 247–252. CrossRef

Wisner, B. (2004) *At risk: Natural hazards, people’s vulnerability and disasters*, Psychology Press, London.

Monitoring flood and drought events – earth observation for multiscale assessment of water-related hazards and exposed elements

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Abstract: Disaster management is dependent on comprehensive information about the hazard's nature and the elements exposed – independent of the location and extent of the hazard. This work explores methods to monitor water-related hazards and identify exposed elements based on multisensorial earth observation (EO) and auxiliary data in southern Africa. For the *hazard-related perspective*, we present methods to monitor floods based on radar data (Sentinel-1, TerraSAR-X) and droughts based on time series MODIS satellite data. For the *exposure-related perspective*, we classify exposed settlements from TerraSAR-X (TSX) and TanDEM-X (TDX) data. We assess people at risk and their respective locations, combining earth observation and census-based geoinformation. The datasets and methods are explored in two case studies investigating a flood in northern Namibia in 2011 and drought events in South Africa and Botswana in 2015 and 2016. The case studies show that the methods developed are crucial tools for hazard and exposure identification, assessment, and monitoring.

Resumo: A gestão de catástrofes está dependente de informação detalhada sobre a natureza do risco e dos elementos expostos, independentemente da localização e da extensão do perigo. Este trabalho explora métodos para a monitorização de riscos relacionados com a água e para a identificação de elementos expostos na África Austral, com base na observação multi-sensorial da Terra (EO) e em dados auxiliares. Para a *perspectiva relacionada com os riscos*, apresentamos métodos para monitorizar cheias, baseados em dados de radar (Sentinel-1, TerraSAR-X), e secas, baseados nas séries temporais dos dados de satélite MODIS. Para a *perspectiva relacionada com a exposição*, classificamos povoados vulneráveis a partir de dados de TerraSAR-X (TSX) e TanDEM-X (TDX). Avaliamos pessoas em risco e as suas respectivas localizações, ao combinarmos a observação da Terra com a geoinformação baseada em censos. Os conjuntos de dados e métodos são explorados em dois casos-de-estudo que examinam uma cheia no Norte da Namíbia em 2011, e eventos de seca na África do Sul e Botswana em 2015 e 2016. Os casos-de-estudo mostram que os métodos desenvolvidos são ferramentas cruciais para a identificação, avaliação e monitorização de riscos e da exposição.

Introduction

Natural hazards have been and will always threaten our societies. Although we have a profound knowledge on historic extreme natural events and their frequency, magnitude or spatial distribution, the earth system is in constant change (Munich Re, 2017). As a consequence, one aspect is climate change, which does not just influence patterns of natural hazards, but also patterns of vulnerability and exposure. At the same time, elements at risk are at constant change. Urbanization processes (Taubenböck et al., 2012) as one example, concentrate more and more people and assets in often hazard-prone areas. However, monitoring the components of risk (Birkmann, 2006), is often limited by temporal and spatial data gaps.

In the past decades, space-borne remote sensing technologies along with geographic information systems (GIS) have become key tools for the assessment of climate change induced risks (Taubenböck et al., 2008). A large body of literature shows, that remote sensing not just holds the capabilities for analyzing hazards such as droughts (Rhee et al., 2010; Winkler et al., 2017) and floods (Martinis et al., 2015; Taubenböck et al., 2009), but also holds the capabilities for deriving exposed elements (Aubrecht et al., 2013; Geiß & Taubenböck, 2013) and assessing the related vulnerability of exposed elements (Geiß et al., 2014). *Exposure* can generally be considered as the location and characteristics of the "elements at risk," *vulnerability* is defined as "the conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of a hazard" (UN/ISDR, 2004).

This study presents the capabilities of multisource earth observation data, techniques, and applications in the context of water-related hazards. We (1) show the potential of rapid mapping activities for reliable spatial assessments of flood impacts at the community level and (2) show the potential for identifying agricultural droughts and quantifying potentially affected elements at national levels.

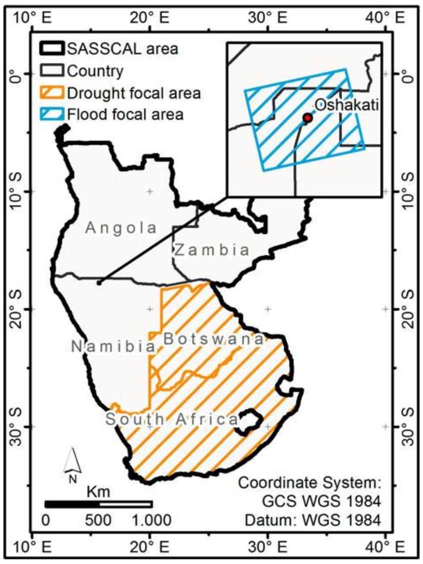

Figure 1: Study area

Study Area

The SASSCAL study area is southern Africa including the countries of Angola, Zambia, Namibia, Botswana, and South Africa (Fig. 1). In this study we work on three different scales: On the *continental scale*, which includes all five southwestern countries of SASSCAL, we monitor water-related hazards and assess potentially exposed elements.

The methods and information gathered on a continental scale are presented in two case studies, of which one is on a national and one on a local scale. The study area on a *national scale* focuses on droughts in 2015–2016 in South Africa and Botswana, whereas the study area on a *local scale* focuses on a flood event in northern Namibia in 2011. This study area, which is located in the most populous area of the Cuvelai-Etosha Basin, covers 143 km² in the Oshana region of Namibia and contains the town of Oshakati, which is the fifth-largest city of Namibia (Mendelsohn et al., 2013).

Data

Regarding hazard management, the availability of reliable, area-wide, up-to-date data is crucial for decision making. In the following we present and give reasons for the selection of a suite of satellite and sociodemographic data for monitoring the specific hazard (floods and droughts) as well as the identification and localization of potentially exposed elements (settlements, people, land cover). Table 1 provides an overview of the data used within this study.

Earth observation data

Satellite data are based on either passive optical systems or active radar (radio detection and ranging) or lidar (light detection and ranging) systems. The selection of the system for specific applications is influenced by various characteristics such as the geometric and temporal resolution. In this study we use radar and optical data for different applications as well as ready-to-use datasets (see Tab. 1).

Hazard-related remote sensing data

Flood

For the detection of surface water and thus, in exceptional circumstances, flooded areas, radar data are often the first choice. In contrast to optical data, they provide continuous all-weather day/night imagery (Brakenridge et al., 2003). In this study we rely on data from the Sentinel-1 mission, operated by the European Space Agency (ESA) in the framework of the European Union's Copernicus Programme. Because floods are relatively short-lived events, a satellite image acquired during and/or shortly after the peak of a flood event is required to obtain up-to-date information. Sentinel-1 is capable of providing this timeliness via a six-day exact repeat cycle and a repeat frequency (ascending/descending) of three days at the equator.

Drought

Since the detection of agricultural droughts using remote sensing is based on different spectral characteristics of healthy and stressed vegetation, optical earth observation (EO) data are applied for the approach suggested here. The assessment of areas affected by droughts was based on 8-day series (MOD09A1) of the moderate resolution imaging spectroradiometer (MODIS). MODIS is a scientific instrument aboard the research satellites Terra and Aqua operated by NASA, and the spatial resolution of the data is 500 meters per pixel (NASA, 2016).

Exposure-related remote sensing data

Settlements

For the classification of potentially exposed human settlements, we use very high-resolution (VHR) synthetic aperture radar (SAR) images of the German TerraSAR-X and TanDEM-X missions that have been collected between 2011 and 2013 (Esch et al., 2013). The vertical spatial resolution is 2 meters (relative) and 10 meters (absolute) within a grid of 12 square meters. Thanks to the globally uniform elicitation and very high resolution, the dataset is very suitable for the computation of settlement areas on a global scale.

Table 1: Multisource geodata applied in this study

Hazard monitoring		Exposure assessment	
Flood	Sentinel 1	Settlements	TerraSAR-X, TanDEM-X
Drought	MODIS	Landcover	Land Cover Map
		Population	WorldPop
		Auxiliary data for test site	In situ population data Infrastructure data

Land cover

The land cover map of the ESA Climate Change Initiative provides a detailed overview of the annual global distribution of land cover types from 1992 to 2015. The spatial resolution of the dataset is 300 meters, and land cover classes were obtained from the processing of the full archives of 300 m MERIS, 1 km SPOT-VEGETATION, 1 km PROBA-V, and 1 km AVHHR surface reflectance 7-day composites. We use this product to assess land cover classes potentially affected by droughts.

Auxiliary sociodemographic data

Besides satellite-based data, we use auxiliary data to assess the exposure and vulnerability of people and elements in both study areas.

For the analyses of sociodemographic situations, we rely on population data originating from the WorldPop project (Tatem, 2017), which provides detailed and open-access population distribution data sets. Peer-reviewed, transparent, and fully documented methods are used to transform and disaggregate population counts at administrative unit levels to 100 m x 100 m grid cells (Tatem, 2017).

While the previous dataset is available for the entire SASSCAL area, we rely for our detailed case study at the local level on in-situ collected population data. They were collected in ground surveys by a mapping team after the 2011 flood in the relevant area.

For the socioeconomic vulnerability analyses, a georeferenced dataset of infrastructure comprising dwelling units and commercial and public services was obtained from the Namibia Statistics Agency (NSA, 2014).

Methods

Hazard-related classification using EO data

The selection of the data and the method of processing the data are strongly dependent on the nature of hazards. Since floods can occur at short notice and droughts, in contrast to this, over long periods of time, different methods of monitoring these events are necessary.

Floods

The Sentinel-1 Flood Service developed at the German Aerospace Center (DLR) is designed for flood detection and monitoring in near-real time (NRT). By user-defined criteria, a Python-based script routinely queries the ESA Sentinel Data Hub for new acquisitions. If the user-defined criteria on location, time, and so on match, the data are automatically downloaded and transferred into a fully automatic processing chain for surface water classification. The workflow consists of geometric correction and radiometric calibration of the Sentinel-1 data, initial classification using automatic thresholding, fuzzy-logic-based classification refinement, and final classification including auxiliary data. The fully automated processing chain allows time-critical disaster information in less than 45 minutes after a new dataset is available. The methodological details are published in Twele et al. (2016).

Droughts

Droughts are conceptually defined as an extended period of deficit rainfall related to the long-term average condition for a specific region (Schneider et al., 2011). Nevertheless, no standard definition of drought exists. The monitoring of spectral information using EO data relies on indices used as proxies to assess the conditions of the vegetation. For the analyses of spatial-temporal patterns of droughts, we used a dataset produced by Winkler et al. (2017). It is based on the Vegetation Condition Index (VCI) calculated from MODIS 8-day series (MOD09A1) of the time period 2000 to 2016. The VCI compares the current NDVI to the values observed in the same time periods in previous years. Lower and higher values (expressed as percentages) indicate bad and good vegetation conditions, respectively (Kogan, 1990). As proposed by Kogan (1995) and widely adopted by the drought-monitoring community (Deng et al., 2013; Gebrehiwot et al., 2011), a threshold of 35% for classifying droughts was applied (Winkler et al., 2017). Phenological information is retrieved from previously generated NDVI time series using the software package TIMESAT 3.2 (Eklundh & Jönsson, 2015). To assess all relevant growing seasons, each dataset refers to an extended year that spans from August of the previous year to December of the current year. In the finally used datasets, the severity of the droughts is indicated by the percentage of time of the growing seasons affected by droughts. More details on the drought dataset and its derivation can be found in Winkler et al. (2017).

Exposure-related classification using EO data

For the classification of human settlements, we use the original backscatter information as well as related texture information in TSX and TDX data. Highly textured surfaces such as vertical settlement structures lead to an increase of directional, non-Gaussian backscatter with comparably high values. In turn, homogeneous surfaces without any true structuring such as grassland show almost no true texture. By this procedure, using local speckle statistics in the SAR data, we localize highly textured regions. Based on this input information, we derive the thematic, binary mask identifying built-up areas and non-built-up areas by analyzing the texture layer by means of a pixel-based image classification procedure (Esch et al., 2013). The localized settlement areas are used as proxy for assessing potentially exposed elements.

Case studies: application of hazard and exposure products

Space defines whether elements are exposed to certain natural hazards, whereas the condition of the elements exposed defines whether they are vulnerable to the specific natural hazard. Based on two case studies, we analyze the elements exposed to a flood and drought event. Regarding droughts, however, it must be considered that people located in areas affected by droughts are not always exposed as a consequence.

Floods

On a local scale we approach the assessment of exposed people and cultivated land related to a flood that occurred in northern Namibia in 2011. Because Sentinel-1A and Sentinel-1B were launched in 2014 and 2016, the flood mask used

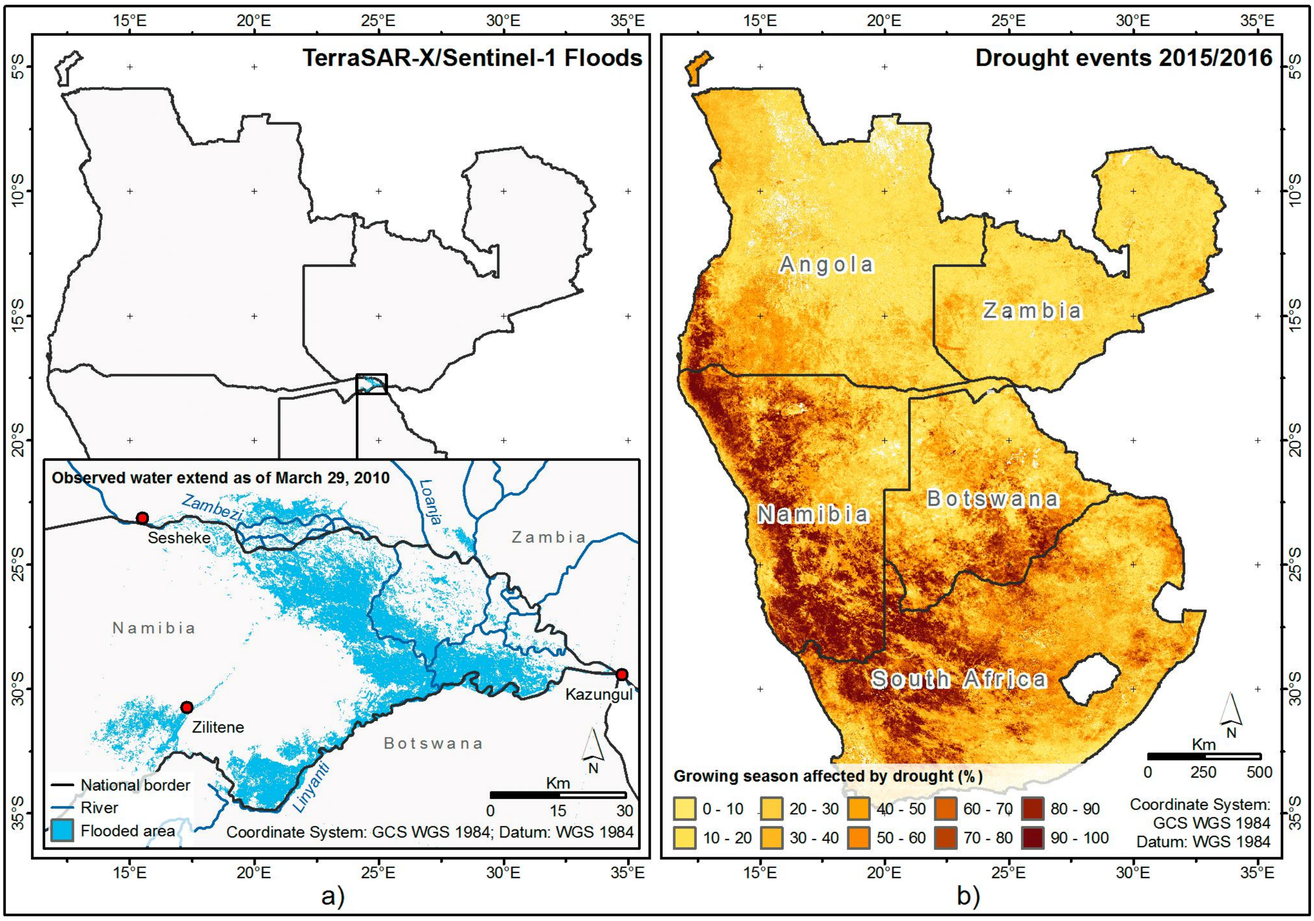

Figure 2: (a) Exemplary extent of water mask processed by TerraSAR-X/Sentinel-1 flood processor and (b) percentage of growing season affected by drought in 2015–2016

in this study was processed by DLR's TerraSAR-X Flood Service (Martinis et al., 2015), which is the previous model of the Sentinel-1 Flood Service. The flood mask displays the extent of the flooded area, including water bodies such as rivers and lakes. To obtain the affected properties and people, the 2011 flood mask, infrastructure data, and population data are intersected for computing geometrically overlapping features. The resulting attribute table is then employed to derive affected properties and number of people.

Droughts

At a national scale we approach the assessment of elements affected by droughts for the countries of South Africa and Botswana. To exemplify the EO-based capabilities, we used 2015/2016 data sets. To define droughts, the observations made from August 2015 to December 2016 were classified into different severity levels. We use four classes (less than 25% of the growing season, 25–50%, 50–75% and more than 75% of the growing season affected by drought events) to assess the severities of droughts. For assessing the exposure of different land cover types to droughts, we compute a spatial overlay analysis localizing the share of different land cover types affected by the drought events.

The population living in areas affected by droughts is derived by a spatial overlay analysis of the percentage of growing season affected by drought and auxiliary population data originating from the WorldPop dataset.

Results

The first section presents the techniques and applications developed to monitor water-related hazards on a continental scale based on multisource earth observation data. Second, datasets generated for exposure assessments in the SASSCAL region are shown. In the last section, the exploitation of the developed methods and generated datasets is presented on the basis of the case studies.

Hazard monitoring in SASSCAL region

Natural hazards feature specific spatial patterns. Figure 2b presents such a specific and distinct pattern for droughts, which occurred between August 2015 and December 2016. A clear spatial grade is illustrated for drought severity across space. Equivalent maps were available for each year between 2000 and 2016, revealing the variability in spatial distributions and extents as well as severities over time. The datasets show the capabilities of multitemporal remote sensing data for monitoring the explicit spatial component of droughts in the SASSCAL region. In the sample year displayed, the western parts of southern Africa are significantly affected during the growing season, while the northern and eastern parts rarely suffer. In addition, Figure 2a illustrates one example of the more than 100 flood events monitored in the area of SASSCAL since 2013. In comparison to droughts, floods are a rather local event. Within the area of SASSCAL, most

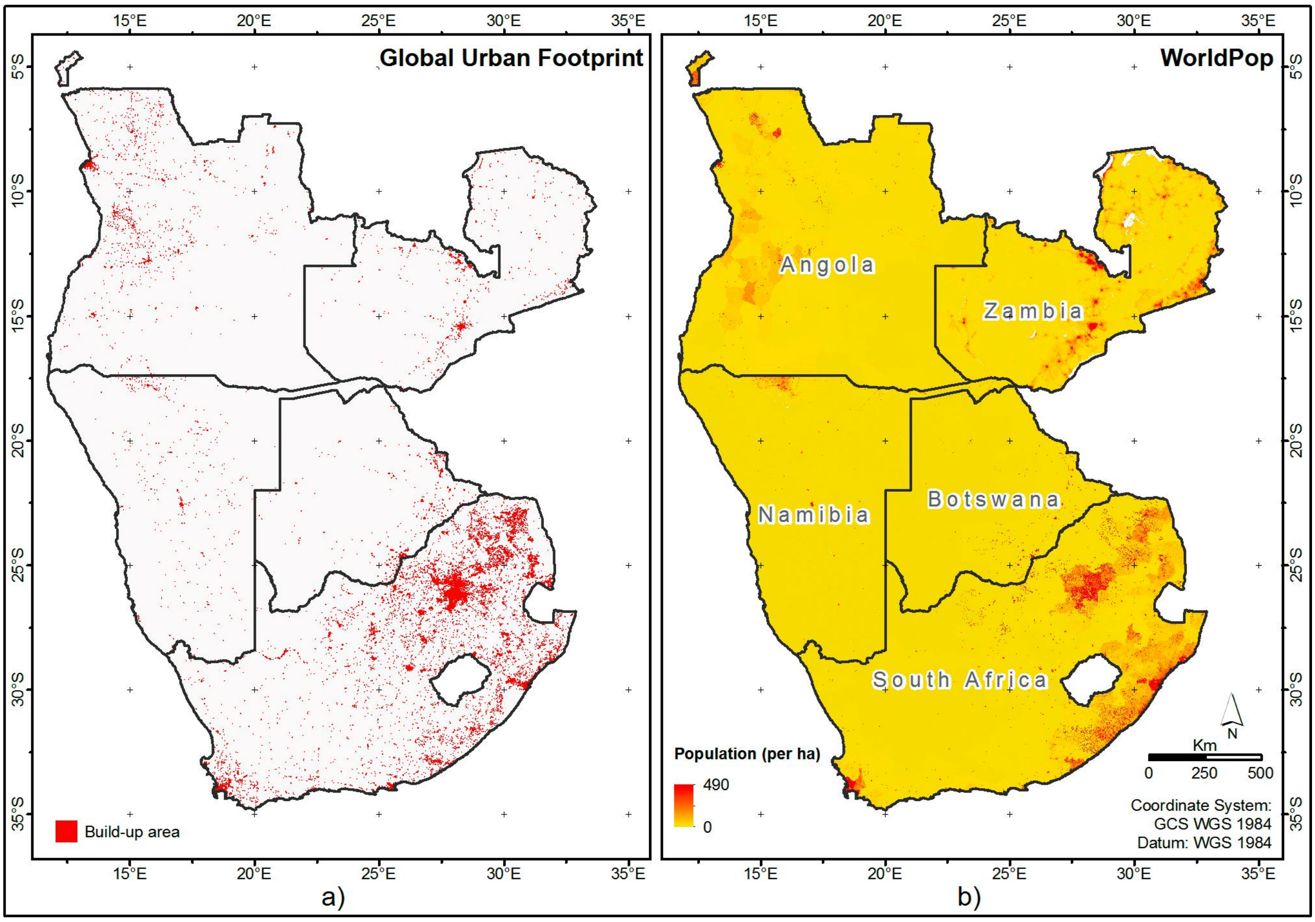

Figure 3: Settlement classification based on (a) the Global Urban Footprint and (b) population density within SASSCAL area based on WorldPop data

observations were made in the Cuvelai-Etosha Basin in the north of Namibia and at the border area between Namibia, Botswana, and Zambia. The floods monitored cover areas ranging from a few square kilometers up to several hectares, such as the one displayed in Figure 2a that stretches over 70 km from north to south and 100 km from east to west.

Exposure assessment in SASSCAL region

As with natural hazards, the exposed elements also feature specific spatial patterns. The classification of settlement distribution (global urban footprint at a spatial resolution of 12 m) is displayed in Figure 3a, indicating the uneven development of human settlements in southern Africa. The clustering of settlements in northeast South Africa with Johannesburg as center reveals this uneven spatial distribution of possibly exposed built environment when compared to, for example, the rural and very low-density settlement areas in Botswana or Namibia.

In addition to the spatial distribution of settlements, the population density is displayed in Figure 3b at a spatial resolution of 1 ha. The comparison of both datasets illustrates similarities and reflects that the spatial clustering of the built environment obviously correlates with population densities; despite the existence of correlation between built-up environment and population densities, however, some differences exist. Overall, these datasets clearly show the capabilities of earth observation data to provide an assessment of exposure on a continental scale.

Local scale analysis: Exposure to water-related hazards

The classifications of hazard- and exposure-related parameters reveal the uneven spatial distribution of each perspective. To assess exposure, we illustrate the capabilities of these geoinformation layers for assessing elements at risk for two examples: a flood event in Namibia in 2011 and drought events in South Africa in 2015.

Flood

Figure 4 presents the distribution of affected properties during the receding stage of the flood, which had peaked two weeks earlier in relation to the April 1, 2011, flood mask. Because Sentinel-1A and Sentinel-1B had been launched in 2014 and 2016, the flood visualized in Figure 4 was processed by the TerraSAR-X flood processor, which is the previous model of the Sentinel-1 flood processor. During that period of the flood on April 1, 2011, Oshakati and its environs had approximately 11,900 properties, of which 270 (2.3%) were still affected by the flood. Almost 90% of the flooded properties were situated in settlement areas, and only 11% were in the countryside. Within the settlement areas, 82% of these properties were in informal settlements, confirming the often proclaimed exposure of the urban poor posited by, for example, Braun and Aßheuer (2011), Davis (2007), and Douglas et al. (2008).

The spatial analysis reveals that 47% of the entire affected building stocks were dwellings. In the period under consideration, the study area had a population of approximately 47,000 residents, out of which 680 (1.5%) were being directly affected. The next most affected (35%) category of properties pertained to demolished structures or vacated dwellings. Commercial properties accounted for 16%, while public services were least affected (less than 1%).

Drought

To assess the impact of droughts, we calculate the share of areas affected by drought of different persistency for four Climate Change Initiative land cover classes (Fig. 5).

In general we found that differences in spatial distributions of droughts and exposed elements led to significant differences in drought hazards in neighboring countries. In Botswana almost 20% of croplands and almost 10% of natural vegetated areas suffered from drought that lasted longer than 75% of the growing season. This is a significantly higher impact than in South Africa, where only 3% of the croplands and 1% of natural vegetated areas suffered this intense drought situation. Nevertheless, the focus should be not on extreme values but on the distribution of the share of the single land cover classes in terms of drought persistency. For example, in Botswana drought persistency above 25% affected more than 20% of cropland (rainfed), while in South Africa less than 5% of the cropland (rainfed) was affected by droughts lasting longer than 75% of the

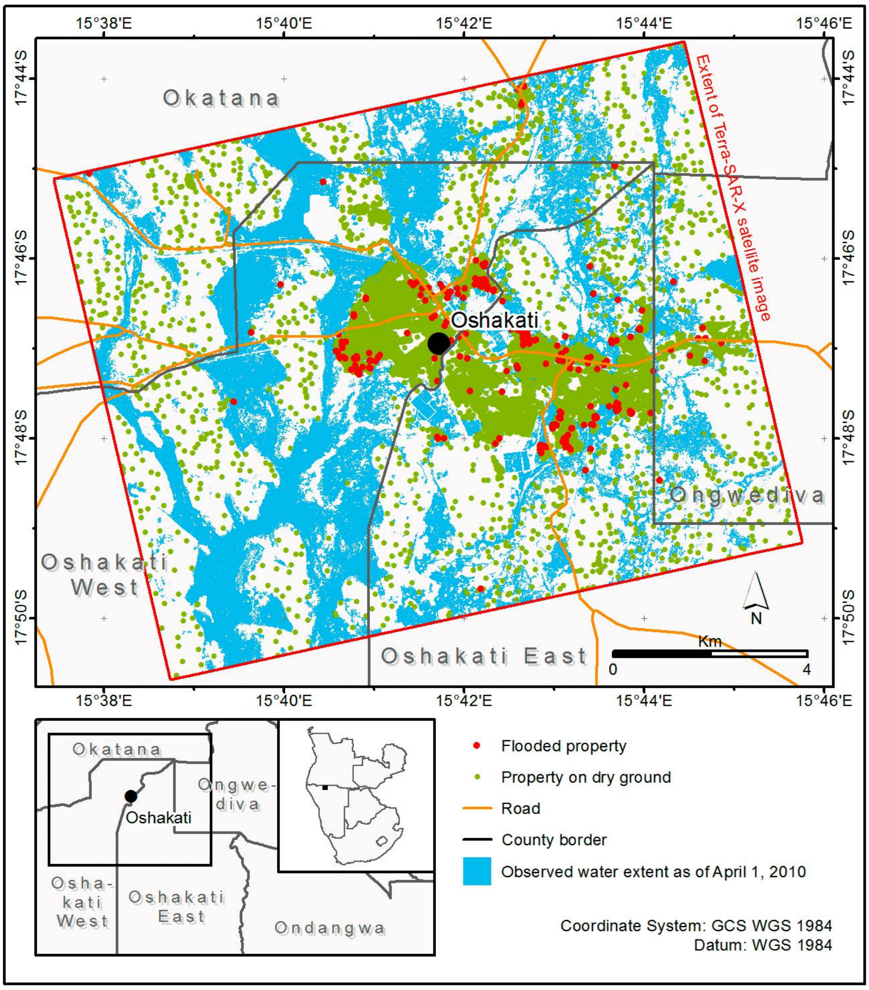

Figure 4: Distribution of flooded properties in and around Oshakati on April 1, 2010, two weeks following the flood peak

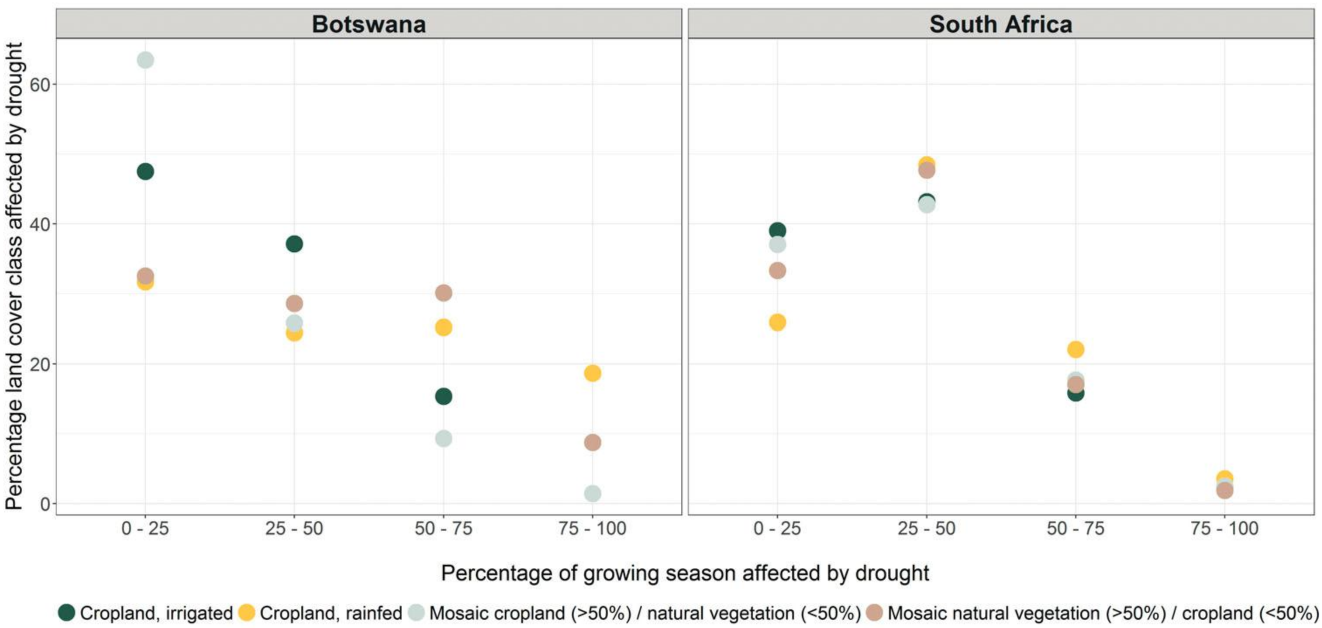

Figure 5: Percentage of land cover classes affected by droughts of different persistency

Table 2: Relative and absolute share of population living in areas affected by droughts of different persistency

Percentage of growing season affected by drought	Botswana		South Africa	
	Population (%)	Population (abs.)	Population (%)	Population (abs.)
0-25%	2.19	46,287	7.1	3,649,307
25-50%	4.74	99,588	11.12	5,710,591
50-75%	7.16	151,402	3.78	1,942,892
75-100%	3.27	69,141	0.5	254,776
Sum	17.33	366,417	22.5	11,557,565

growing season. Additionally to the share of affected land cover, we calculated the share of the population living in affected areas differentiated in accordance with drought persistency (Tab. 2).

In both countries most people living in areas of investigated land covers were affected by droughts that lasted for 25% to 75% of the growing season (Botswana, 11.9% of the total population; South Africa, 14.9% of the total population). Because of the difference in total population numbers, the absolute number of people living in areas affected by droughts during 25% to 75% of the growing season is 30 times greater in South Africa (7.5 million) than in Botswana (about 250,000). Nevertheless, comparing the population living in areas affected by droughts lasting longer than 50% of the growing season, the relative population affected is higher in Botswana (10.4%) than in South Africa (4.3%).

Discussion

Earth observation data in combination with other geodata are capable of detecting and monitoring water-related hazards and identifying exposed elements. The study reveals the immense capability of multisensorial and multitemporal remote sensing applications for identifying and evaluating different components of risk spatially for large areas as well as in high spatial and thematic detail.

In general, remote sensing allows assessment of risk with high accuracy; it must be considered, however, that remote sensing methods do not produce cadastral data sets with respect to accuracy. Also, vegetation parameters used as proxies to assess droughts may not provide a perfect match. Thus, the methods of deriving flood masks, monitoring droughts, and classifying land cover can be optimized using better-calibrated algorithms or different, higher-resolution datasets, or by extending thematic information (e.g., by assessing flood depth in addition to flood extent). For example, studies dealing with flood or settlement detection based on EO data revealed that accuracies are in the range of 80–90% (Klotz et al., 2016; Martinis et al., 2015), which allow assessment with high reliability. The following discussion sheds light on the capabilities of EO data in terms of *hazard management*, the *value of the developed methods* and *derived datasets*. Furthermore, the discussion focuses on the benefits and challenges of applying EO data in managing hazards.

Mapped floods derived from freely available EO data, which are independent of weather condition and daylight, provide information of unique spatial scale and resolution. EO data enable the monitoring of floods on a continental scale and can provide information about the spatial extent of floods within a few hours. Nevertheless, the temporal resolution of Sentinel-1 data in Africa is not as high as stated by the European Space Agency; we observed that the temporal resolution ranges from a few weeks to a couple of days depending of the area of interest in the SASSCAL region. The importance of the timeliness of the data in case of floods is also highlighted in the case study. Because of runoff, high evaporation rates, and permeability, the flood extent captured two weeks after the flood peak inevitably underestimates the impacted infrastructure and number of people. Nevertheless, it reveals the persistence of the flood impact, which is crucial for flood damage assessment. In our study case, people in informal settlements were identified as the most affected, partly as a result of the fact that they often (have to) settle in marginalized areas, including flood-prone zones. The high number of demolished or vacated dwellings in and around Oshakati may be attributed to earlier displacement from the previous floods that took place in the area for two consecutive years, 2009–2010 (Mendelsohn et al., 2013). Even if additional datasets – as in this case study – were not available, the settlement classification based on the Global Urban Footprint and the population data from WorldPop provide sufficient information about hot spots affected by floods.

For people involved in hazard management, the results of the exposure analysis (settlement distribution and population data) can easily be made available, and the case studies show that EO data are capable of providing a unique overview of hazardous situations.

Climate is changing, and to be able to adapt to these changes it is crucial to monitor the changing systems. In contrast to monitoring floods, the aim of monitoring drought is to gain knowledge in order to address the following question: What areas are most affected with respect to spatial extent, persistency, and intensity of droughts? In the case study, the growing seasons of two countries are compared as an example; the long-term data obviously allow much more research on various spatial and temporal scales. In general, one limitation of the drought dataset used in this study is its spatial resolution of 500 meters. As a matter of fact, the spatial resolution of the data used limits the ability to detect droughts on, for example, scattered small-sized fields surrounded by other land cover types (e.g., irrigated fields, natural vegetation). However, medium-resolution data such as MODIS are to date the only available satellite data that provide sufficient and consistent time series to be used to assess anomalies and thus drought. As soon as longer high-resolution time series (e.g., Landsat-8, Sentinel-2) become available within the next few years, there will be new potential for assessing drought at a higher spatial resolution. Although the data do not consist of information about the impact of these droughts on the population, the data are crucial for long-term analysis.

Climate change comes with an increasing frequency and intensity of extreme events. Those require instruments for rapid monitoring to support hazard management and thus well-founded decisions by stakeholders. Climate change also comes with long-term changes. EO data are capable of providing information on both of these temporal scales. Therefore, the methods developed provide data not only in the short term but also in the long-term, which helps us understand changing systems.

Conclusion

In general, earth observation data and techniques feature immense potential for identifying, assessing, and monitoring water-related hazards. The obvious and necessary extension in the future will be the increase in information content. High-resolution digital surface models might allow assessments of flood depth, new missions such as Sentinel will increase the spatial resolution of drought monitoring (He et al., 2016), and very high-resolution optical satellite data increase the thematic resolution of, for example, settlements into structural types such as business districts or slums (Taubenböck & Kraff, 2014). Beyond, in the time of "big data", the combination with other geodata – as exemplified here with population and socioeconomic data – holds immense capabilities for more comprehensive perspectives on hazards, exposure, vulnerability, and ultimately risks. Data sources of relevance include census, open geoinformation, and social media data. In conclusion, the new advent of data offers immense capabilities for better geoinformation for risk management; however, the methodologies and the topic-adpated useful applications still need to be developed.

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References

Aubrecht, C., Fuchs, S. & Neuhold, C. (2013) Spatio-temporal aspects and dimensions in integrated disaster risk management. *Natural Hazards*, **68**, 1205–1216.

Birkmann, J. (Ed.). (2006) Measuring vulnerability to natural hazards: towards disaster resilient societies. United Nations University, Tokyo.

Brakenridge, G.R., Anderson, E., Nghiem, S.V. Caquard, S. & Shabaneh, T.B. (2003) *Flood warnings, flood disaster assessments, and flood hazard reduction: the roles of orbital remote sensing*. Proceedings of the 30th International Symposium on Remote Sensing of Environment, Honolulu, Hawaii.

Braun, B., & Aßheuer, T. (2011) Floods in megacity environments: vulnerability and coping strategies of slum dwellers in Dhaka/Bangladesh. *Natural Hazards*, **58**, 771–787.

Davis, M. (2007) *Planet of slums*. Verso, London.

Deng, M., Di, L., Han, W., Yagci, A.L., Peng, C. & Heo, G. (2013) Web-service-based monitoring and analysis of global agricultural drought. *Photogrammetric Engineering & Remote Sensing*, **79**, 929–943.

Douglas, I., Alam, K., Maghenda, M., Mcdonnell, Y., McLean, L. & Campbell, J. (2008) Unjust waters: climate change, flooding and the urban poor in Africa. *Environment and Urbanization*, **20**, 187–205.

Eklundh, L. & Jönsson, P. (2015) TIMESAT: a software package for time-series processing and assessment of vegetation dynamics. *Remote sensing time series* (ed. by C. Kuenzer, S. Dech, and W. Wagner), pp. 141–158. Springer International Publishing, Switzerland.

Esch, T., Marconcini, M., Felbier, A., Roth, A., Heldens, W., Huber, M., Schwinger, M., Taubenböck, H., Müller, A. & Dech, S. (2013) Urban footprint processor – fully automated processing chain generating settlement masks from global data of the TanDEM-X mission. *IEEE Geoscience and Remote Sensing Letters*, **10**, 1617–1621.

Gebrehiwot, T., van der Veen, A. & Maathuis, B. (2011) Spatial and temporal assessment of drought in the Northern highlands of Ethiopia. *International Journal of Applied Earth Observation and Geoinformation*, **13**, 309–321.

Geiß, C. & Taubenböck, H. (2013) Remote sensing contributing to assess earthquake risk: from a literature review towards a roadmap. *Natural Hazards*, **68**, 7–48.

Geiß, C., Taubenböck, H., Tyagunov, S., Tisch, A., Post, J. & Lakes, T. (2014) Assessment of seismic building vulnerability from space. *Earthquake Spectra*, **30**, 1553–1583.

He, L., Qin, Q., Ren, H., Du, J., Meng, J. & Du, C. (2016) Soil moisture retrieval using multi-temporal Sentinel-1 SAR data in agricultural areas. *Transactions of the Chinese Society of Agricultural Engineering*, **32**, 142–148.

Klotz, M., Kemper, T., Geiss, C., Esch, T. & Taubenböck, H. (2016) How good is the map? a multi-scale cross-comparison framework for global settlement layers: evidence from Central Europe. *Remote Sensing of Environment*, **178**, 191–212.

Kogan, F.N. (1990) Remote sensing of weather impacts on vegetation in non-homogeneous areas. *International Journal of Remote Sensing*, **11**, 1405–1419.

Kogan, F.N. (1995) Application of vegetation index and brightness temperature for drought detection. *Advances in Space Research*, **15**, 91–100.

Martinis, S., Kersten, J. & Twele, A. (2015) A fully automated TerraSAR-X based flood service. *ISPRS Journal of Photogrammetry and Remote Sensing*, **104**, 203–212.

Mendelsohn, J., Jarvis, A. & Robertson, T. (2013) *A profile and atlas of the Cuvelai-Etosha basin*. RAISON, Windhoek, Namibia.

Munich Re. (2017) *Natural catastrophes 2016. Analyses, assessments, positions*. Munich Re, München, Deutschland.

NASA. (2016) *Moderate resolution imaging spectroradiometer.*

NSA. (2014) *Namibia population and housing census 2011*.

Rhee, J., Im, J. & Carbone, G.J. (2010) Monitoring agricultural drought for arid and humid regions using multi-sensor remote sensing data. *Remote Sensing of Environment*, **114**, 2875–2887.

Schneider, S.H., Root, T.L. & Mastrandrea. M.D. (2011) Encyclopedia of climate and weather, 2nd edition. Oxford University Press, Oxford.

Tatem, A.J. (2017) WorldPop, open data for spatial demography. *Scientific Data*, **4**, 170004.

Taubenböck, H., Esch, T., Felbier, A., Wiesner, M., Roth, A. & Dech, S. (2012) Monitoring urbanization in mega cities from space. *Remote Sensing of Environment*, **117**, 162–176.

Taubenböck, H., Goseberg, N., Setiadi, N., Lämmel, G., Moder, F., Oczipka, M., Klüpfel, H., Wahl, R., Schlurmann, T., Strunz, G., Birkmann, J., Nagel, K., Siegert, F., Lehmann, F., Dech, S., Gress, A. & Klein, R. (2009) Last-mile preparation for a potential disaster – interdisciplinary approach towards tsunami early warning and an evacuation information system for the coastal city of Padang, Indonesia. *Natural Hazards and Earth System Science*, **9**, 1509–1528.

Taubenböck, H. & Kraff, N. (2014) The physical face of slums: a structural comparison of slums in Mumbai, India, based on remotely sensed data. *Journal of Housing and the Built Environment*, **29**, 15–38.

Taubenböck, H., Post, J., Roth, A., Zosseder, K., Strunz, G. & Dech, S. (2008) A conceptual vulnerability and risk framework as outline to identify capabilities of remote sensing. *Natural Hazards and Earth System Sciences*, **8**, 409–420.

Twele, A., Cao, W., Plank, S. & Martinis, S. (2016) Sentinel-1-based flood mapping: a fully automated processing chain. *International Journal of Remote Sensing*, **37**, 2990–3004.

UN/ISDR. (2004) *Living with risk: A global review of disaster reduction initiatives*. United Nations Publications, Geneva, Switzerland.

Winkler, K., Gessner, U. & Hochschild, V. (2017) Identifying droughts affecting agriculture in Africa based on remote sensing time series between 2000–2016: rainfall anomalies and vegetation condition in the context of ENSO. *Remote Sensing*, **9**, 831.

References [CrossRef]

Aubrecht, C., Fuchs, S. & Neuhold, C. (2013) Spatio-temporal aspects and dimensions in integrated disaster risk management. *Natural Hazards*, **68**, 1205–1216. CrossRef

Birkmann, J. (Ed.). (2006) Measuring vulnerability to natural hazards: towards disaster resilient societies. United Nations University, Tokyo.

Brakenridge, G.R., Anderson, E., Nghiem, S.V. Caquard, S. & Shabaneh, T.B. (2003) *Flood warnings, flood disaster assessments, and flood hazard reduction: the roles of orbital remote sensing*. Proceedings of the 30th International Symposium on Remote Sensing of Environment, Honolulu, Hawaii.

Braun, B., & Aßheuer, T. (2011) Floods in megacity environments: vulnerability and coping strategies of slum dwellers in Dhaka/Bangladesh. *Natural Hazards*, **58**, 771–787. CrossRef

Davis, M. (2007) *Planet of slums*. Verso, London.

Deng, M., Di, L., Han, W., Yagci, A.L., Peng, C. & Heo, G. (2013) Web-service-based monitoring and analysis of global agricultural drought. *Photogrammetric Engineering & Remote Sensing*, **79**, 929–943. CrossRef

Douglas, I., Alam, K., Maghenda, M., Mcdonnell, Y., McLean, L. & Campbell, J. (2008) Unjust waters: climate change, flooding and the urban poor in Africa. *Environment and Urbanization*, **20**, 187–205. CrossRef

Eklundh, L. & Jönsson, P. (2015) TIMESAT: a software package for time-series processing and assessment of vegetation dynamics. *Remote sensing time series* (ed. by C. Kuenzer, S. Dech, and W. Wagner), pp. 141–158. Springer International Publishing, Switzerland.

Esch, T., Marconcini, M., Felbier, A., Roth, A., Heldens, W., Huber, M., Schwinger, M., Taubenböck, H., Müller, A. & Dech, S. (2013) Urban footprint processor – fully automated processing chain generating settlement masks from global data of the TanDEM-X mission. *IEEE Geoscience and Remote Sensing Letters*, **10**, 1617–1621. CrossRef

Gebrehiwot, T., van der Veen, A. & Maathuis, B. (2011) Spatial and temporal assessment of drought in the Northern highlands of Ethiopia. *International Journal of Applied Earth Observation and Geoinformation*, **13**, 309–321. CrossRef

Geiß, C. & Taubenböck, H. (2013) Remote sensing contributing to assess earthquake risk: from a literature review towards a roadmap. *Natural Hazards*, **68**, 7–48. CrossRef

Geiß, C., Taubenböck, H., Tyagunov, S., Tisch, A., Post, J. & Lakes, T. (2014) Assessment of seismic building vulnerability from space. *Earthquake Spectra*, **30**, 1553–1583. CrossRef

He, L., Qin, Q., Ren, H., Du, J., Meng, J. & Du, C. (2016) Soil moisture retrieval using multi-temporal Sentinel-1 SAR data in agricultural areas. *Transactions of the Chinese Society of Agricultural Engineering*, **32**, 142–148.

Klotz, M., Kemper, T., Geiss, C., Esch, T. & Taubenböck, H. (2016) How good is the map? a multi-scale cross-comparison framework for global settlement layers: evidence from Central Europe. *Remote Sensing of Environment*, **178**, 191–212. CrossRef

Kogan, F.N. (1990) Remote sensing of weather impacts on vegetation in non-homogeneous areas. *International Journal of Remote Sensing*, **11**, 1405–1419. CrossRef

Kogan, F.N. (1995) Application of vegetation index and brightness temperature for drought detection. *Advances in Space Research*, **15**, 91–100. CrossRef

Martinis, S., Kersten, J. & Twele, A. (2015) A fully automated TerraSAR-X based flood service. *ISPRS Journal of Photogrammetry and Remote Sensing*, **104**, 203–212. CrossRef

Mendelsohn, J., Jarvis, A. & Robertson, T. (2013) *A profile and atlas of the Cuvelai-Etosha basin*. RAISON, Windhoek, Namibia.

Munich Re. (2017) *Natural catastrophes 2016. Analyses, assessments, positions*. Munich Re, München, Deutschland.

NASA. (2016) *Moderate resolution imaging spectroradiometer.*

NSA. (2014) *Namibia population and housing census 2011*.

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Schneider, S.H., Root, T.L. & Mastrandrea. M.D. (2011) Encyclopedia of climate and weather, 2nd edition. Oxford University Press, Oxford. CrossRef

Tatem, A.J. (2017) WorldPop, open data for spatial demography. *Scientific Data*, **4**, 170004. CrossRef

Taubenböck, H., Esch, T., Felbier, A., Wiesner, M., Roth, A. & Dech, S. (2012) Monitoring urbanization in mega cities from space. *Remote Sensing of Environment*, **117**, 162–176. CrossRef

Taubenböck, H., Goseberg, N., Setiadi, N., Lämmel, G., Moder, F., Oczipka, M., Klüpfel, H., Wahl, R., Schlurmann, T., Strunz, G., Birkmann, J., Nagel, K., Siegert, F., Lehmann, F., Dech, S., Gress, A. & Klein, R. (2009) Last-mile preparation for a potential disaster – interdisciplinary approach towards tsunami early warning and an evacuation information system for the coastal city of Padang, Indonesia. *Natural Hazards and Earth System Science*, **9**, 1509–1528. CrossRef

Taubenböck, H. & Kraff, N. (2014) The physical face of slums: a structural comparison of slums in Mumbai, India, based on remotely sensed data. *Journal of Housing and the Built Environment*, **29**, 15–38. CrossRef

Taubenböck, H., Post, J., Roth, A., Zosseder, K., Strunz, G. & Dech, S. (2008) A conceptual vulnerability and risk framework as outline to identify capabilities of remote sensing. *Natural Hazards and Earth System Sciences*, **8**, 409–420. CrossRef

Twele, A., Cao, W., Plank, S. & Martinis, S. (2016) Sentinel-1-based flood mapping: a fully automated processing chain. *International Journal of Remote Sensing*, **37**, 2990–3004. CrossRef

UN/ISDR. (2004) *Living with risk: A global review of disaster reduction initiatives*. United Nations Publications, Geneva, Switzerland.

Winkler, K., Gessner, U. & Hochschild, V. (2017) Identifying droughts affecting agriculture in Africa based on remote sensing time series between 2000–2016: rainfall anomalies and vegetation condition in the context of ENSO. *Remote Sensing*, **9**, 831. CrossRef

The Extreme Climate Index (ECI), a tool for monitoring regional extreme events

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The Extreme Climate Index (ECI) is an objective, multi-hazard index capable of tracking changes in the frequency or magnitude of extreme weather events in Africa. The index is geared towards identifying broad-scale climate extremes that may affect several countries at once and could impact food security as well as countries' individual ability to manage such events. The index is intended to be included in the climate index insurance scheme by African Risk Capacity (ARC) towards calculation of payouts.

The index is calculated per 2.5° grid points across Africa. The index is calculated from two observational datasets. These are the NCEP Reanalysis (Kalnay et al., 1996) daily temperature data together with the CHIRP (Climate Hazards Group InfraRed Precipitation; Funk et al., 2015) dataset for monthly rainfall. The higher-resolution rainfall dataset (0.05° spatial resolution) is resampled to the coarse resolution of the temperature data.

To identify extreme conditions, the ECI is calculated by combining a rainfall- and a temperature-based index:

- The Standardized Heat Index (SHI): Calculated from daily maximum temperature, considering maximum temperature relative to the statistical distribution of the historical time series.
- The Standardized Precipitation Index (SPI; McKee et al., 1993): Derived from monthly rainfall data. The SPI has been used widely and is considered to be a robust representation of the rainfall situation for any location with a historical rainfall dataset.

Based on the variability of rainfall as represented by the three-month SPI, seven large homogenous areas are identified through cluster analysis (Fig. 1). For each cluster, the index is calculated separately. The mean of the SPI per cluster and the mean of the SHI per cluster, per day, are standardized. The combination of these standardized input indices allows for the identification of various types of extreme conditions such as cold and wet, warm and dry, warm and wet, etc., per cluster.

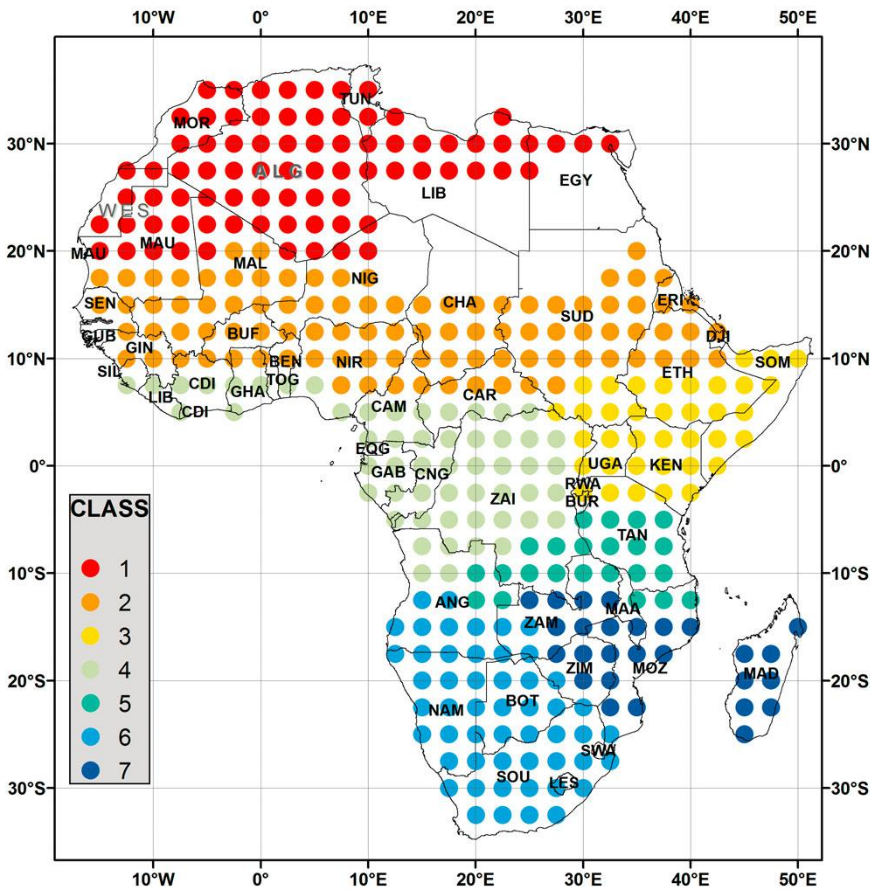

Figure 1: Climate clusters for the ECI across Africa, obtained by adopting the three-month Standardized Precipitation Index (SPI) as an underlying cluster object to identify relatively homogenous zones.

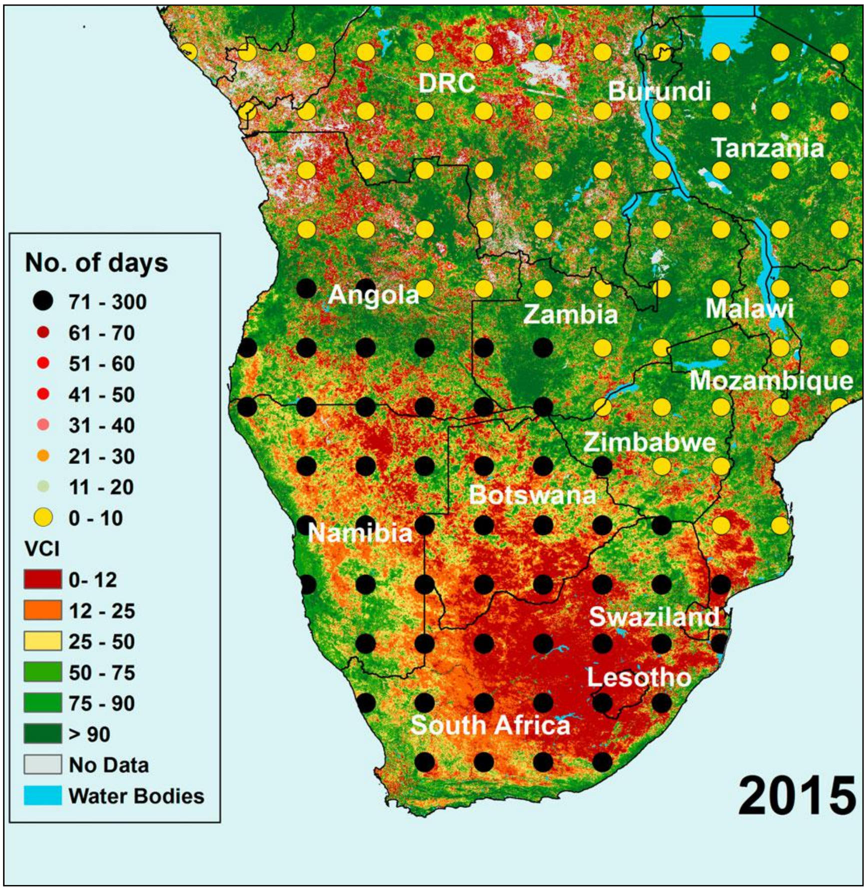

Figure 2: Vegetation Condition Index (VCI) by late December 2015 (green-to-brown colours) overlain by the 2.5° ECI grid (dots) indicating the number of days during 2015 when the index reached extreme values (> 95th percentile). Warm colours of the VCI indicate vegetation stress (here related to drought).

The Council for Scientific and Industrial Research (CSIR) in South Africa and SASSCAL evaluated the potential of anthropogenic climate forcing to influence the behaviour of the index through the 21st century. Towards this end, we consider also the ability of the index to identify extreme events under current conditions. Utilizing various evaluation datasets for southern and eastern Africa such as disaster relief, river flow, and crop production data, the index identified the most extreme events since 1982 with an accuracy of 72%.

The most recent drought over large parts of southern Africa occurred during the summer of 2015/2016 (Archer et al., 2017). During this drought event, the largest rainfall deficits occurred during October to December 2015, resulting in largest negative effects on vegetation activity already by December 2015. The map in Figure 2 shows the ability of the ECI to identify the most severely affected areas as indicated by drought-related vegetation stress by late December 2015.

To identify drought-related stress, the Vegetation Condition Index (VCI; Quiring & Ganesh, 2010) is shown in green to brown colours. The legend was chosen to identify vegetation stress in brown. It is clear that the most severe stress, over a wide region, occurred across South Africa, Botswana, and Namibia. The VCI is overlain by the 2.5° gridded ECI, showing the number of days per ECI cluster (Fig. 1) during 2015, when the index reached extreme values (> 95th percentile). It demonstrates how the index correctly identified, at a regional scale, the most affected area as shown by an unrelated vegetation index.

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References

Archer, E.R.M., Landman, W.A., Tadross, M.A., Malherbe, J., Weepener, H., Maluleke, P. & Marumbwa, F.M. (2017) Understanding the evolution of the 2014–2016 summer rainfall seasons in southern Africa: Key lessons. Climate Risk Management, 16, 22-28.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A. & Michaelsen, J. (2015) The climate hazards infrared precipitation with stations — a new environmental record for monitoring extremes. Scientific Data, 2, p.150066.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J. & Zhu, Y. (1996) The NCEP/NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society, 77, 437–471.

McKee, T.B., Doeskin, N.J & Kleist, J. (1993) The relationship of drought frequency and duration to time scales. Proceedings of the 8th Conference on Applied Climatology, January 17–22, 1993, pp. 179–184. American Meteorological Society, Boston, MA, USA.

Quiring, S.M. & Ganesh, S. (2010) Evaluating the utility of the Vegetation Condition Index (VCI) for monitoring meteorological drought in Texas. Agricultural and Forest Meteorology, 150, 330–339.

Risk management

Are large classical gully systems inactive remnants of the past? A field-based case study investigating sediment movement

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Abstract: The Swartland region in the Western Cape of South Africa is situated in a Mediterranean climate zone, affected by large gullies that are widespread in occurrence on commercial farms. Despite gully erosion being recognized as a major land degradation process, especially in Mediterranean climates, these large gully scars in the Swartland are believed to be inactive remnants of the past. Due to this belief, gully erosion research in the Swartland is a topic that has long been ignored. To address this research shortfall, a field-based case study of a classic, discontinuous gully system in the Swartland was done. Sediment movement was measured at hillslope scale and discussed in the context of rainfall data and field observations of gully activity. The results showed that the gully system was an active sediment source, but also a conduit for sediment from hillslopes. Notably, ploughed contour banks, a measure introduced to curb gully erosion, are causing the expansion of the gully network, in addition to delivering sediment from hillslope sources to the gully system. Vegetation cover was found to reduce gully erosion temporally by up to 91.6% during the case study period. This case study illustrates that large gully channels are not mere relics of the past, but complex erosive systems that require further field-based investigations to develop an understanding of the dynamics involved.

Resumo: A região de Swartland, localizada no Cabo Ocidental na África do Sul, situa-se numa zona de clima mediterrâneo, afectada por grandes ravinas que ocorrem com frequência em quintas comerciais. Apesar da erosão das ravinas ser reconhecida como um processo significativo de degradação do solo, em especial nos climas mediterrâneos, acredita-se que estas grandes cicatrizes em Swartland são vestígios inactivos do passado. Devido a esta crença, a pesquisa sobre a erosão das ravinas de Swartland é um tema há muito ignorado. De modo a abordar esta carência de investigação, foi realizado um caso-de-estudo de um sistema clássico e descontínuo de ravinas em Swartland. O movimento dos sedimentos foi medido na escala de vertente e discutido no contexto de dados de precipitação e observações de campo da actividade das ravinas. Os resultados mostraram que o sistema de ravinas é uma fonte activa de sedimentos, como também um veículo para os sedimentos das vertentes. Notavelmente, os bancos de contorno arados, medida introduzida para controlar a erosão das ravinas, estão a causar a expansão desta rede, além de adicionarem sedimentos das vertentes aos sistemas de ravinas. A cobertura vegetal reduziu a erosão temporariamente até 91,6% durante o período do caso-de-estudo. Este demonstrou que as grandes ravinas não são apenas relíquias do passado, mas sim sistemas complexos de erosão que necessitam de mais investigação de campo para se desenvolver uma compreensão das dinâmicas envolvidas.

Introduction

Gully erosion is regarded as a severe land degradation process worldwide (Valentin *et al*., 2005). Gully formation occurs when concentrated surface water or subsurface water flow removes soil, causing incised channels to form (Kirkby and Bracken, 2009). These channels rapidly evolve into an interconnected network of gully channels, resulting in severe soil loss with various deleterious consequences (Sidorchuk, 1999). These negative consequences associated with gully erosion have an impact both at the source of a gully, on-site, and further in the catchment, off-site. On-site consequences mostly affect land resources that include the removal of fertile topsoil and biomass, which results in loss in soil quality and productivity. Simultaneously, gully erosion causes large landscape scars resulting in mosaic plots that increase farming costs (Valentin *et al*., 2005). Off-site impacts mostly affect water resources. Sediment causes a reduction in downstream water quality that adversely affects eco-system health (Chaplot *et al*., 2005; Hancock and Evans, 2006). Furthermore, increased amount of sediment can cause a loss of storage capacity of rivers and dams that leads to decrease in water availability, in addition to increasing the likelihood of flooding (Boardman, 2006; Le Roux and Sumner, 2012). Given the severity and extent of these negative consequences, it is imperative to further our understanding of gully erosion.

With recent technological advancements, there has been a shift from field-based work to remote, desktop modelling of gully erosion to assess gully density and dynamics. Remote work provides a platform to investigate gully erosion on a large spatial resolution at low cost. As a result of the aforementioned benefits, remote investigation is deemed an appropriate solution to assess the degree of gully erosion to help formulate regional strategies for land managers for sustainable land practises (Mararakanye and Le Roux 2012). Caution should be exercised so as not to conduct remote investigations prematurely. Gully erosion is a highly complex, systematic threshold phenomenon with numerous factors driving gully evolution at any given time (Nordstrom, 1988). Only with an understanding of gully erosion dynamics, insight can be gained into gully evolution that will aid the formulation of appropriate strategies for land managers. Classical fieldwork is a prerequisite to gain an understanding of gully erosion dynamics before remote modelling can successfully be applied. Castillo and Gómez (2016) emphasised this need for classical fieldwork to fill knowledge gaps in gully erosion and specifically indicated the need to address the scarcity of research on whole gully networks on hillslope scale under actual rainfall conditions.

The Swartland region in the Western Cape in South Africa (SA) was selected as a case study to investigate a whole gully network on hillslope scale, utilizing actual rainfall data through a combination of empirical field observations and in-field experiments. Gully erosion research in the Swartland is limited to an extensive survey that included classical fieldwork by Talbot (1947) and remote investigations by Morrel (1998), Meadows (2003) and more recently Olivier *et al.* (2016). Land-use change to extensive wheat cultivation in the 1930's caused severe gully erosion, but the landscape recovered due to soil conservation methods recommended by Talbot (1947). Follow-up studies by Morel (1998) and Meadows (2003) confirmed a marked reduction in gully erosion. The only signs still indicative of the historical gully problems in Swartland are numerous large gully scars found on main drainage lines and man-made contour banks throughout the Sandspruit catchment (Steudel *et al*. 2015). Meadows (2003) indicates that the large gully channels still found in the Swartland are inactive relics of past gullies, formed during the 1930's, with the only reason for its existence *in situ*, due to difficulty in removing it as the gullies were eroded to the bedrock. Farmers in the Swartland share this sentiment and believe these large gully systems to be inactive. Olivier *et al.* (2016) created a remote classification system to collect baseline information as a first step to conduct gully erosion research by using GeoEye-1 stereo imagery obtained in 2011. During this investigation bare gully channels were identified. Available data is, however, inadequate to verify whether the bare gully channels are indicative of active gully processes or whether it is merely a sign of a lack of vegetation. Since the Swartland is extensively used for agriculture and vital to the region's food security, it is imperative to investigate these large gully scars to identify

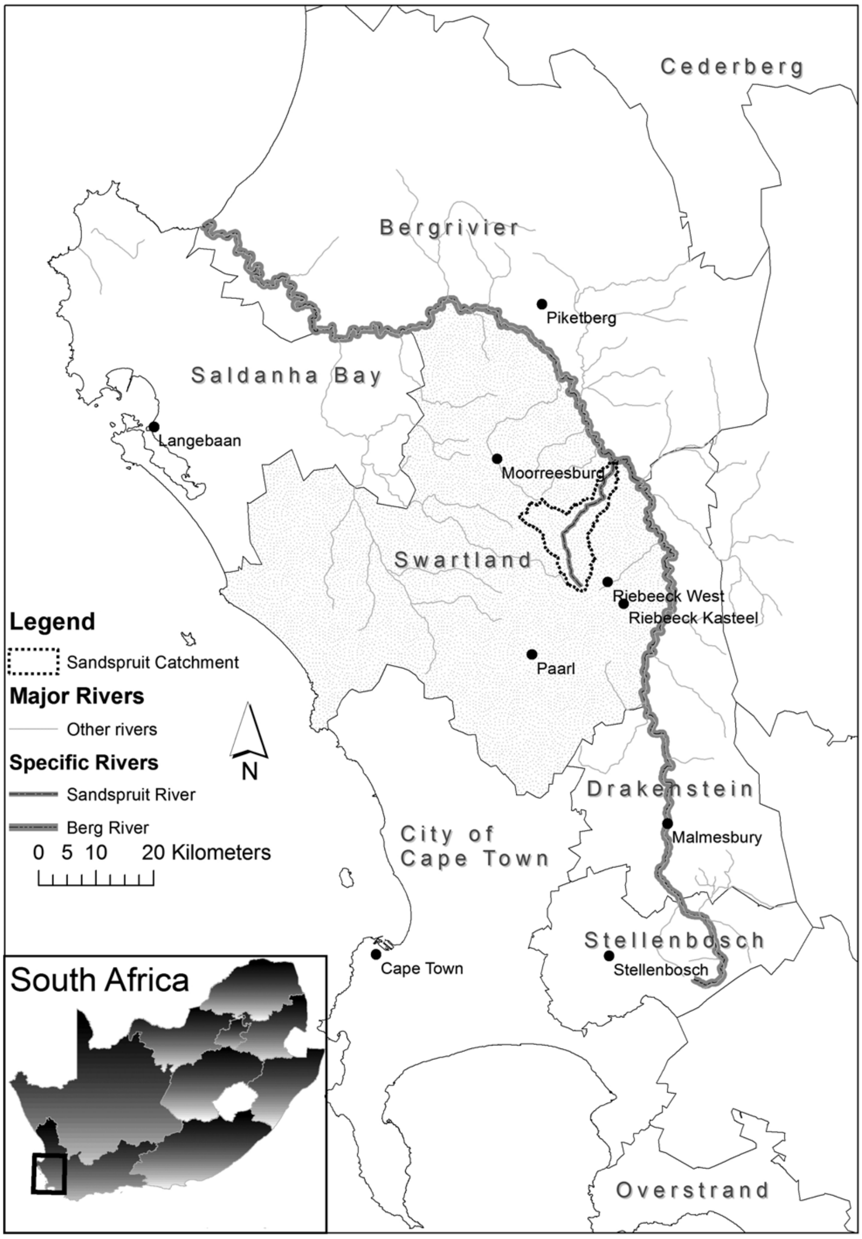

Figure 1: Sandspruit catchment

whether it is still active. Additionally, the Swartland has a unique Mediterranean climate; one of only two such climatic zones in Africa. Mediterranean environments have been strongly associated with gully erosion by numerous authors (e.g. Poesen and Hooke, 1997; Poesen *et al.*, 2003; Valentin *et al.*, 2005; De Baets *et al.*, 2009). Poesen *et al.,* (2002) found that gully erosion contributes between 50– 80% of sediment yield in semi-arid Mediterranean environments.

The goal of this study is to investigate gully activity within one of these remnant, inactive gully scars in the Swartland region. The focus will be on identifying active processes thus indicating sediment source areas that will provide insight into gully evolution. This type of data could not only prove insightful, but also actionable, providing land managers with a means to implement appropriate mitigating strategies to limit gully erosion or rehabilitate gully prone areas.

Figure 2: Gully network at Malansdam and initial observations**:** *1) Boundary fence could have led to initial gully formation, 2) Gullies are currently expanding behind contour banks, 3) Tillage method used can cause increase amount of runoff leading to the gully expansion behind contour banks, 4) numerous gully channels at steep slope (4b) when compared to gentle slope (4a).*

Methods

Study site

The study site is the Sandspruit catchment, a tributary of the Berg River basin, which is located in the Swartland and approximately 152 km2 in extent (Figure 1). The Swartland region has a Mediterranean type climate with dry summers and wet winters. Annual rainfall varies between 400 and 750 mm, of which 80% occurs during winter, mostly due to cyclonic cold fronts (Meadows, 2003). The landform consists of gentle undulating hills with the only prominent mountain being Kasteelberg at the southerly tip of the Sandspruit catchment, with height above mean sea level ranging between 30 and 950 m (Steudel et al., 2015). The underlying geology is quite monotonous, consisting mostly of Malmesbury shale that was deposited during the pre-Cambrian period (Bugan et al., 2012). Lithic Glenrosa soil derived from Malmesbury shale dominates the Sandspruit catchment, accounting for 70% of soils (Steudel et al., 2015). These soils are characteristically course to medium textured with a low organic carbon content (usually less than 0.4%), resulting in a soil with low stability that is highly erodible. Furthermore, de Clercq et al. (2010) found the soils to be highly saline increasing its vulnerability to erosion.

Observations from the case study site

A discontinuous, split channel gully network on Malansdam farm (Figure 2) was selected as the case study site. The gully network is located on a commercial wheat farm, within a thin sliver of Renosterveld. From initial observations, the gully shows signs that its origins are of anthropogenic nature. The main gully channel is found along the main drainage line where a fence was installed (Figure 2, along line drawn at position 1) – most likely during the 1930's during the land-use change to wheat cultivation. The fence line is hypothesized as the origin of the gully network, which contributed to gully erosion in two ways: 1) Livestock and vehicles moving along the fence; 2) Contour construction. Cattle and vehicles moving along the fence line would have compacted soil increasing vulnerability to soil erosion by limiting infiltration resulting in a higher volume of overland flow. Ploughed contours were introduced as a measure to curb soil erosion by reducing slope length on cultivated fields, but resulted in the generation of channelized overland flow towards the main drainage line. A higher volume of water would therefore have accumulated and flowed along the main drainage line at the fence, where soil was compacted. Ploughed contours, a measure implemented to prevent soil erosion by farmers, influenced gully evolution and appear to have played a key role in initiating this gully network. Observational evidence suggest that ploughed contours are continuing to influence gully evolution, discernible by bank gullies extending behind contours into the cultivated field (Figure 2, various positions labelled 2). The effect of slope on gully erosion is also evident in Figure 2, with numerous gully channels at the forefront of the picture (Position 3a), with the gully network fading into one channel where slope is gentle (Figure 2, position 3b).

Methodology

A time-series of aerial photographs and satellite imagery from 2000 to 2017 was created as an initial assessment of temporal changes in gully activity. A georeferenced aerial photograph from 2000 was used in conjunction with GeoEye-1 stereo imagery from 2011 and georeferenced satellite imagery from the Google Earth

Pro platform for 2005 and 2017. These images were overlaid with ArcGIS 10.4.1 to allow a visual inspection by switching layers on and off. This provided a rapid assessment of any extensive geomorphic changes of the gully network. In addition to this, a topographical map from 1944 was used to determine the erosion base level and origin of the gully network.

Fieldwork consisted of installing perforated sediment traps in nine different gully channels, before the start of the winter, on 13 April 2012. The sediment traps, with a diameter of 110 mm and depth of 300 mm, were inserted into the gully channel floor in the flow path with the uppermost part of the sediment trap being level with the gully floor (Figure 3). After installation, sediment was collected at four points in time.

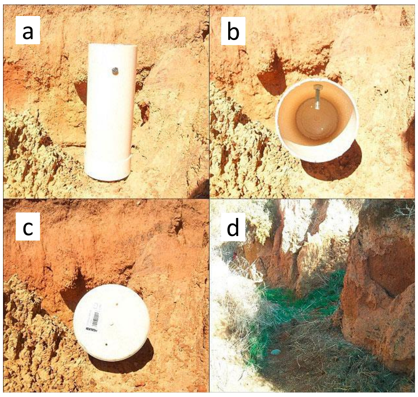

Figure 3: Perforated sediment traps installed in the gully channels at Malansdam: (a) Depicts a side view with the depth being 300mm; (b) top view with a diameter of 110mm; (c) indicates the perforated bottom to allow water drainage; (d) installed sediment trap installed level with surface and in line with the water flow path.

During installation, various attributes were noted:

- GPS position was recorded for each installation point. The GPS positions were loaded into ArcGIS 10.4.1 to calculate the total gully length in meters upstream of the sediment trap by making use of the digitised gully system from Olivier et al. (2016).
- Observations regarding activity were made based on criteria set by Oostwoud Wijdenes et al. (2000) that linked gully activity with gully geomorphological observations (Table 1). For a gully channel to qualify as active it had to display any combination of two or more of the active criteria, as each criterion given, except for piping, is interlinked. Similarly, a gully channel was classified as being inactive when it had a combination of any two (or more) of the non- active criteria, as these factors are evidence of stabilisation.

Table 1: Observational criteria to assess gully activity

Active	Not Active
Sharp edges	Rounded edges
Plunge pool	No plunge pool
Undercut	Inclined gully head wall
Tension cracks	Vegetation on gully walls and bed
Recently deposited sediment	Extremely small contributing catchment area
Flow marks	
Piping	

Hourly rainfall data for the winter of 2012 was obtained from a field weather station situated in the Sandspruit catchment at Langewens farm. The hourly measurements allowed both rainfall quantity and rainfall intensity to be related to sediment movement in the gully network.

Results

During rapid assessment of the remotely sensed imagery time-series from 2000–2017, no geomorphic changes of the gully network was visualised. When comparing the 1944 topographical map and the time series, no change in base level was evident, as the discontinuous gully fades into a depositional zone near farm dwellings that had to be erected prior 1944. In-field observations indicated that gully processes were active. Figure 4 shows a bank gully extending away from the primary gully on a dirt farm road. Recent activity is noticeable from both gully channels, looking at the collapsed soil found in the gully along the walls and the head. The bank gully has a channel extending towards the vehicle most likely fed by increased overland flow, due to the compaction of the soil on the dirt road.

Numerous bank gullies with active gully heads behind ploughed contours were found throughout the extent of the gully network. These bank gullies had a variety of sizes and occurred in a systematic manner, behind ploughed contour banks.

Figure 4: Bank gully expansion along farm dirt road

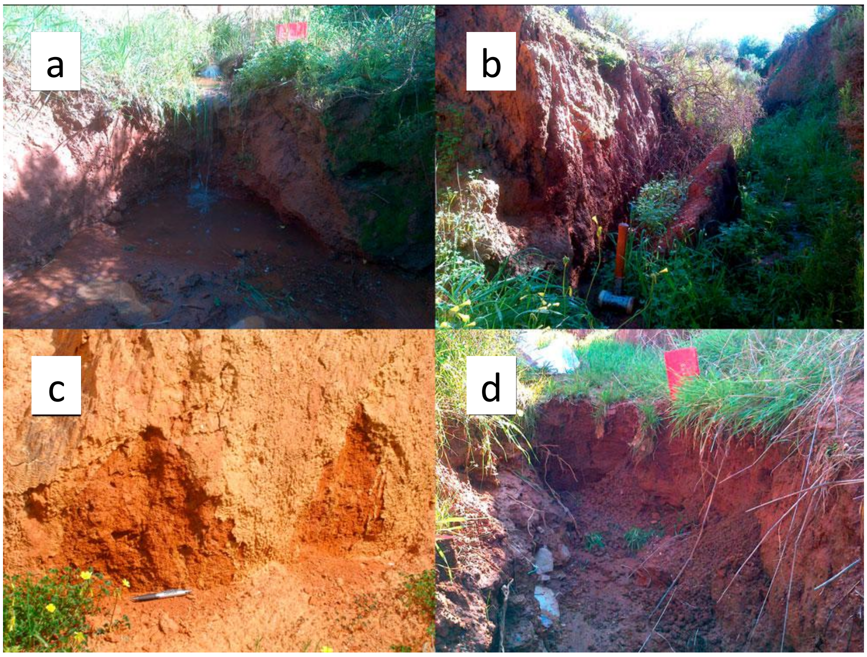

Figure 5: Active gully processes*: a – gully sidewall collapse as the gully wall became undercut due to waterflow within the gully; b – gully sidewall collapse due to tension cracks; c – gully headward retreat in action; d – newly established gully within a large established gully channel leading to gully deepening.*

Table 2: Observational and measured data for sampled gully channels

Gully number -	Gully activity*	Gully channel length (in m)	Sediment yield (in g)			
			Period 1: 13 April-16 June	Period 2: 17 June-16 July	Period 3: 17 July-16 August	Period 4: 17 August-24 September
1	Not active	10	91.2	8.6	0	0
2	Active	9	119.2	69.6	161	105.6
3	Active	30	887.2	712.2	512.4	349.2
4	Active	23	1883.8	514.5	752.1	96.3
5	Active	34	1423.7	0	177.9	145.3
6	Active	131	1624.7	2045.7	1493.9	125.3
7	Active	171	252.4	29.6	196.6	53
8	Active	721	563	588.2	0**	138.7
9	Active	1468	5272.9	4283.4	2512.9	0***
	TOTAL SY		12118.1	8251.8	5806.8	1013.4

**Activity determined from observations in field as per criteria in Table 2*
*** Sample contaminated with decomposing mouse.*
**** Sediment trap was damaged irreparably.*

Table 3: Rainfall characteristics for each collection period

	Rain days	Total rainfall (mm)	Hourly high (mm)	24 hour maximum (mm)	2-day high (mm)	2-day rainfall events*	3-day high (mm)	3-day rainfall events**
Period 1	21	92.2	5.8	18.0	27.6	6	28.0	1
Period 2	15	54.8	8.4	10.8	12.6	3	15.8	2
Period 3	16	77.8	7.0	19.6	20.8	5	25.6	1
Period 4	17	48.0	4.8	12.2	13.0	3	13.6	2

** amount of times 2 continuous days of rainfall occurred*

*** amount of time 3 days of consecutive rainfall was observed*

Figure 5a shows one such a bank gully after a rainfall event. The active plunge pool causes the gully head to become undercut in addition to sharp edges are indicative of an active gully. After prolonged activity, the bank gully would extend laterally along the ploughed contour via headward retreat. In addition to bank gullying, other active widening processes were observed. Gully wall collapse occurred in numerous magnitudes. Figure 5b and c indicate the opposite ends of the scale with Figure 5b showing a collapsed wall visible on the gully floor, whilst Figure 5c shows a small-scale gully wall collapse episode due to tension cracks. Both of these collapsing events were deduced as recent activity due to the darker colourisation of the freshly exposed soil on the gully wall.

Whilst Figures 5a-c offer evidence of active gully widening, evidence was also found that indicated gully deepening. Figure 5d shows a recent, active smaller gully channel found within a larger established gully channel. This phenomenon occurred numerous times throughout the gully network.

Eight of the nine gully channels where sediment traps were installed were deemed active upon application of the criteria in Table 2. Sediment trap 9 was installed in close proximity, downstream of a newly developed, smaller, active gully headcut found in the main gully channel (in Figure 5d). Data about activity, sediment yield and gully length is given in Table 2.

A variety of gully channel lengths were sampled with the shortest channel measured at 9 m and the longest as 1468 m. Sediment was trapped during the first 2 periods for the non-active gully channel, where after it became dormant. The largest amount of sediment was trapped in sediment trap 9 that was installed downstream of the active gully head for the first 3 periods. As winter progressed, sediment total sediment collected decreased from 1211.1 g to 1013.4g.

A dry winter was experienced in the Swartland during the case study, with 272.8mm of rainfall measured from period 1 to 4, compared to the average winter rainfall of 400 and 750 mm (Meadows, 2003). Since short, high intensity, rainfall and long, low intensity rainfall both promote gully erosion, intensity in addition to longer durational rainfall events (2-day and 3-day rainfall events) were investigated. Rainfall characteristics for each collection period are summarised in Table 3.

The highest 24-hour rainfall period was 19.6 mm on 11 August during period 3. The most rain days, 21 days, and the highest total rainfall, 92.2 mm, occurred during period 1. Six 2-day rainfall events were observed during period 1, with the highest 2-day rainfall event accumulating 27.6 mm from 7–8 June. The highest intensity rainfall event occurred on 30 June during period 2 with a rainfall depth of 8.4 mm h-1 recorded. Two 3-day rainfall events occurred during period 2 and 4, whilst only one occurred during periods 1 and 3. The highest accumulating 3-day rainfall event accumulated a rainfall depth of 28.0 mm during period 1.

Discussion

Active gullying or inactive remnants of the past

This case study sought to determine whether seemingly historical remnant gully scars found in the Swartland are only remnants of historically unsustainable cultivating practises or still actively eroding systems. These pervasive gully scars were instigated when Renosterveld was extensively removed to make way for intensified wheat cultivation in the Swartland prior 1930's (Meadows, 2003) Gully channel formation is a rapid process after gully initiation Sidorchuk, 1999). It is hypothesised that gullies, including the gully network investigated in this case study, developed rapidly due to land-use change in the 1930's. The process of gully initiation and development at Malansdam is described in the Methods section. This is supported by hand drawn maps from Talbot (1947) that indicate severe gullying in the Kasteelberg area in close proximity to Malansdam. Since Talbot's (1947) survey, the Swartland landscape has recovered markedly (Morrel, 1998; Meadows, 2003), which can be attributed to soil conservation recommendations made by Talbot (1947). One such recommendation that was used to mitigate gully erosion was ploughing contours; it was used widely and in the Swartland there is estimated to be 25 000 km of ploughed contours (Meadows, 2003). The initial time-series that was created by imagery from 2000 to 2017 no significant geomorphic changes were observed, supporting the findings of Morrel (1998) and Meadows (2003). Sediment was however trapped during the study period confirming sediment movement through the gully network, suggesting sediment yield from a source elsewhere, as oppose to active gully processes (Rowntree, 2014).A similar sequence of events occurred, in the Sneeuberg region of the Karoo in SA. Gullying was initiated due to land-use change in conjunction of the occupation of the European settlers (Rowntree, 2014; Boardman et al., 2017). According to Boardman et al. (2017), gullies have not extended significantly since 1945, thus reaching a stable state. Instead, these large gully scars are acting as conduits for sediment from badlands and hillslopes. The role of these gullies have thus changed from being a sediment source due to active gully processes to providing effective transport channels for sediment from hillslopes to valley bottoms. Evidence from the time-series imagery and sediment yield indicates that the gully network at Malansdam is, as Rowntree (2014) described, an evil sluit / gully acting as a conduit, rapidly transporting sediment from hillslope sources.

Classical fieldwork conducted during this case study contradicts the above findings that the gully network is stable and acts as a conduit for sediment from hillslope sources only. Active gully processes causing widening and deepening of the gully network were observed. Tension cracks were found, but it is a small-scale process unable to account for the quantity of sediment trapped. Three major sediment sources were identified that could account for the sediment yield: 1) gully wall collapse, 2) bank gullies and 3) smaller gully systems within the larger confines of the gully network. Recent gully wall collapse episodes were observed, which is a large-scale event that causes sediment to be deposited on the gully floor and thereafter to be transported during flow periods. . Gully wall collapse was mostly observed in the upper reaches of the gully network, where near vertical gully walls are exhibited. During the study period 17 2-day rainfall events and 6 3-day rainfall events occurred. These sustained periods of rainfall would cause the near vertical gully walls to become unstable and collapse. Martínez-Casasnovas et al. (2004), similarly, found gully wall collapse to be a major sediment source in large established gully networks. Within existing gully networks, numerous newly propagating smaller gullies, were observed. These smaller gullies exhibit the same gully dynamics as a typical, individual gully. Sediment trap 9 was placed downstream of the headcut of one of these smaller gullies, trapping a large amount of sediment. This makes sediment yield estimations difficult as these smaller gully systems would actively erode large quantities of sediment at the gully head, only to be deposited elsewhere in confines of the gully network. Sediment yield from sediment trap 9 did indicate that these smaller gully systems are an important sediment source. Numerous bank gullies that extend behind ploughed contours were found to have active headcuts. Currently, contour banks are being counter intuitive and instead of curbing soil erosion, seems to be channelling overland flow towards the main gully network, driving gully evolution via headward retreat. These earthen structures are acting like embankments that Cooke and Reeves (1976) emphasized in playing a role in gully erosion due to concentrating overland flow and increasing hydraulic power. At this gully network, it is especially problematic as higher volumes of water are being diverted higher up in the gully network. This enables an increase in erosive power, since a larger volumes of water is diverted towards the gully network where a steeper gradient is exhibited. In addition to sediment yield, the bank gullies extending behind the ploughed contours creates mosaic field units, thereby increasing cost to farmers. Classical fieldwork found, contradictory to the remote work, that the gully network is still producing sediment via numerous active gully processes

Risk management

With the remote work indicating stability and classical fieldwork identifying active gully erosion processes, the question remains: Is the gully network active or an old remnant of the past? The active gully processes is not a form of renewed gullying as no base level changes were observed nor did any anthropogenic or environmental changes occur from 2000–2017. The active gully processes observed during fieldwork would thus have been active during the period of the time-series from 2000–2017. Yet no detectable levels of soil loss on the time-series imagery can be identified. This case study finds that current gully erosion levels can be deemed negligible and potential remedial costs by the farmer would outweigh soil loss incurred through gully erosion.

Sediment yield-Rainfall relationship

Although a drier winter was experienced during the case study, normal frontal rainfall events did occur. Similar rainfall characteristics were recorded for periods 1 and 3, and periods 2 and 4. Due to the rainfall characteristics being comparable, sediment yield should correspond with rainfall, producing similar sediment yield for periods 1 and 3, and 2 and 4. There is, however, no correlation between rainfall and sediment yield, with sediment yield decreasing by 91.6% during the case study. A reduction of 52.1% in sediment yield was calculated for periods 1 and 3, and a reduction of 87.7% between periods 2 and 4 (Figure 5 and 6 shows the decreasing trend of sediment yield versus some of the rainfall trends during the case study period).

Vegetation growth can potentially explain the disparity between sediment yield and rainfall trends. Numerous authors have demonstrated that vegetation plays a key role in reducing gully erosion (Francis and Thornes, 1990; Rey, 2003; Chen and Cai, 2006). More specifically Beuselinck et al. (2000), in addition to Gyssels and Poesen (2003) found that grass and wheat, the same vegetation found in the gully network at Malansdam, resulted in an exponential decrease in erosion rates in a Mediterranean environment. In the Swartland, soil will be

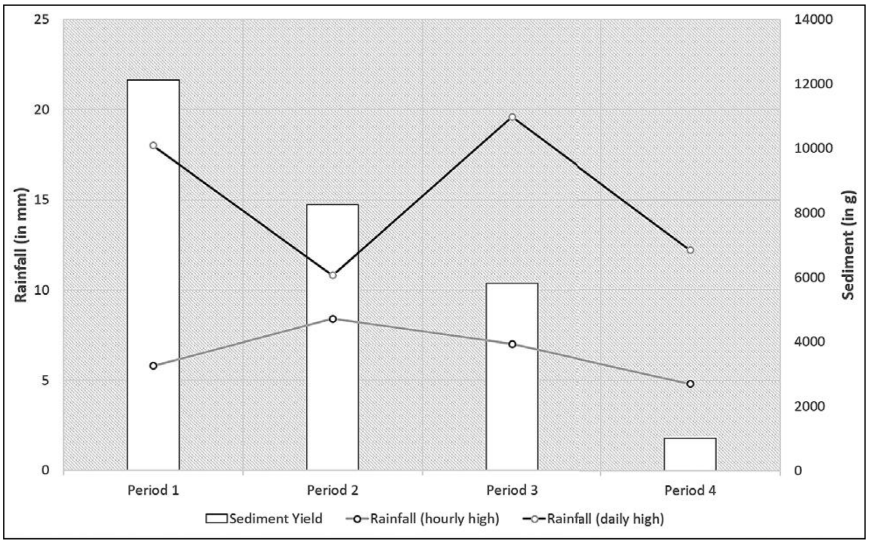

Figure 6: Sediment yield *versus* daily rainfall trends for each collection period

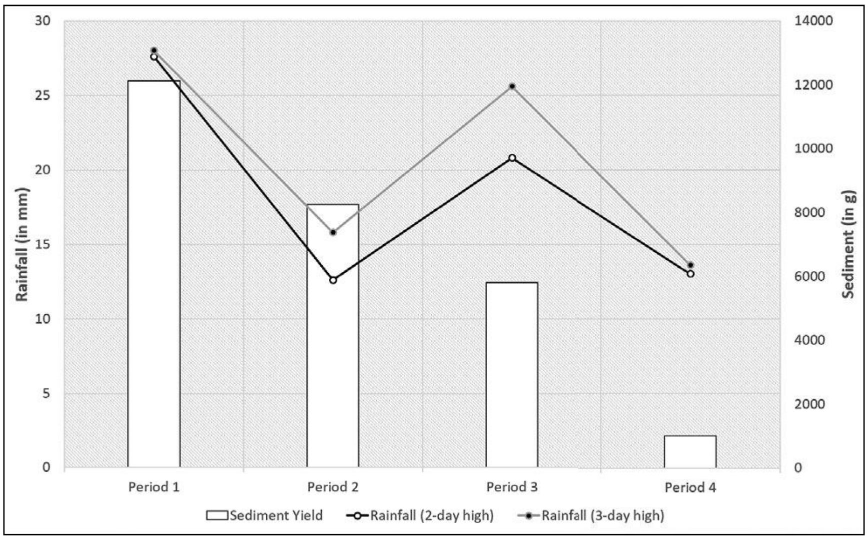

Figure 7: Sediment yield *versus* highest continuous rainfall depth for 2 and 3 consecutive days per period

at most risk to gully erosion during late autumn and early winter when soil is bare prior the start of the winter rainfall season. Natural vegetation and wheat follow a similar growth profile since wheat is a rainfed crop in SA. Gully channels will be bare due to summer aridity, in addition to the hillslopes as wheat is generally planted between May and mid-June (DAFF, 2017). Short, intense rainfall or longer durational, low intensity rainfall would therefore have a higher erosion potential during period 1, which is why the largest amount of sediment was produced during this stage. Sediment yield in period 1 would therefore be sediment from hillslopes transported via overland flow along the ploughed contours, and active gully erosion processes found in the gully network. After initial rainfall, vegetation in the gully channel would emerge and tillering phase of wheat growth will be reached. Minimum vegetation cover can thus be expected during period 2. During periods 3 to 4 vegetation cover reached 100% cover in the gully channels, with wheat reaching maturity. Vegetative trapping ability of sediment thus incrementally increased as the case study period progressed, explaining the sharp decrease in sediment yield found in the gully network at Malansdam. Figure 8 shows the bare channels observed at the beginning of the study period versus vegetated channels and fields at the end of the case study.

Even though vegetation was strongly linked to reduced gully erosion in this case study, Figure 8 indicates the temporary nature of the protection it offers. Vegetative growth only acts as a temporary store for newly generated sediment from hillslopes and active gully processes. As the vegetation in the gully network dies back during the summer, its trapping ability diminishes, resulting in stored sediments to be susceptible to erode due to water flow through the gully network. Betts et al. (2003) found that small rainfall events are required for these dormant, temporary sediment stores to be "flushed" down a gully system.

While the vegetative growth explains the reduction in sediment yield during the case study period, the temporary nature of the trapping ability of vegetation could also explain large sediment yields in period 1. Since vegetation buffers sediment yield, sediment from dormant stores can still be cycled through the gully network in addition to sediment yield from bare gully channels and hillslopes. The sediment stores could also explain the presence of smaller gully systems found in the established gully network, as gully heads can form at sediment stores where significant sediment eroded after vegetation has died off, resulting in the formation of a gully head, within the larger gully channel. From evidence in this case study, planting perennial grass in gully channels and along ploughed contours can promote stability, as it will inhibit gully erosion and impede on its ability to act as a conduit.

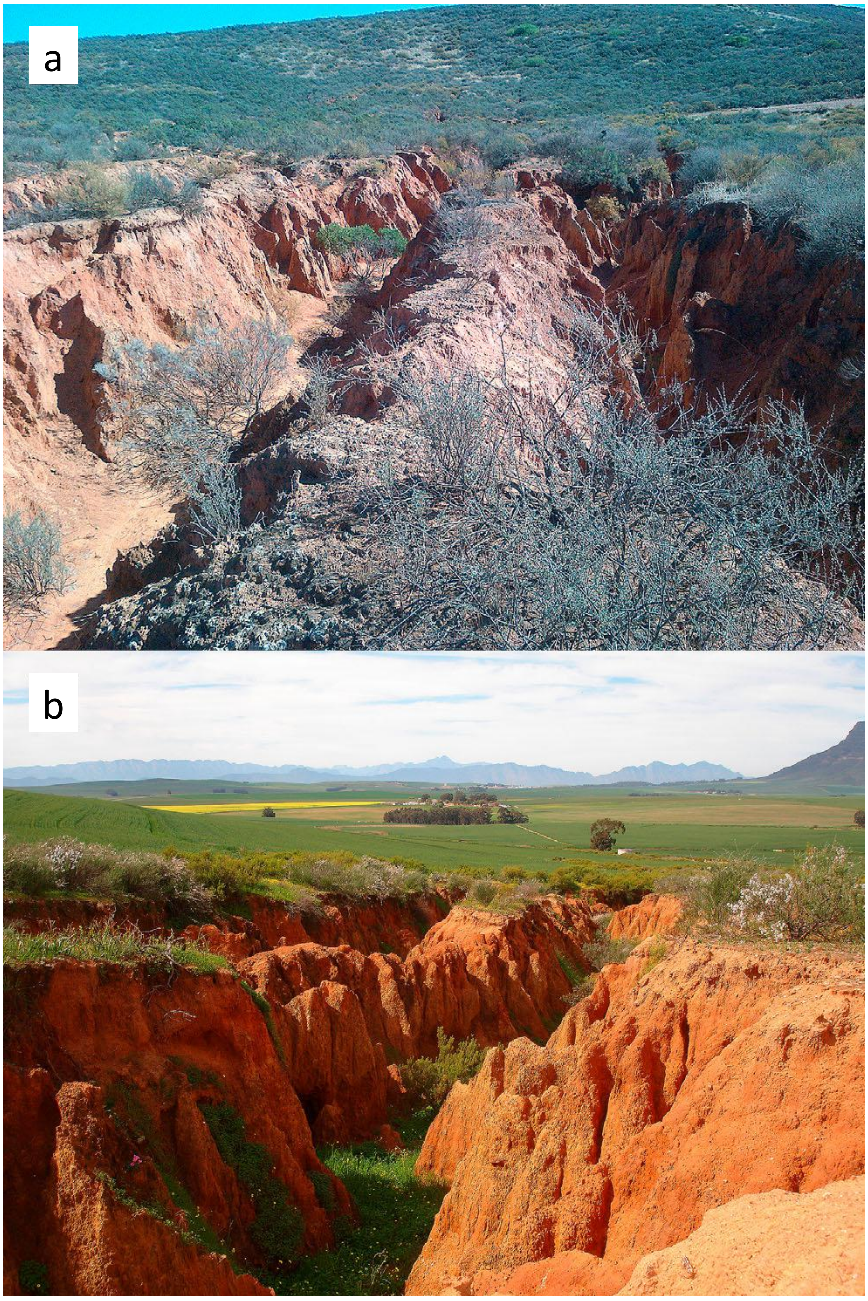

Figure 8: Temporal vegetation cover in the MGS: a) bare gully channels observed during sediment trap installation prior winter; b) gully channels fully covered by grass and wheat, in addition to wheat cover on the hillslope at the end of the case study

Conclusion

Notably, this case study found that ploughed contours played a contributory role in the initiation and evolution of the gully network at Malansdam. This is worrying, especially since 25 000km of ploughed contours are found in the Swartland. Numerous bank gully channels with active headcuts were found extending behind these earthen structures established by farmers to reduce soil erosion. This is problematic for two reasons: 1) the active gully channel extending behind the ploughed contour shows that overland flow is directed towards the gully channel. This will promote sediment delivery from hillslopes to the gully network, which will be transported to the valley floor; 2) Active gully channels can retreat headward, as it will have a continuous supply of overland flow during rainfall events causing the gully channels to extend further into the cultivated field units. The gully extension will induce larger soil losses and increase farming costs as it will create mosaic field units.

During this investigation active gully processes incurring soil losses were observed, but a time series of imagery from 2000–2017 indicated no observable gully extension. Unfortunately, headward retreat was not measured during this case study and are not able to compare headward retreat rates with the remote observations. Such an experiment could yield interesting results. Currently, the large gully scars were found to be in a state of stability, despite active gully processes being observed in the field. Any costs incurred by remedial work will currently outweigh cost of soil loss.

According to climate data from (Meadows, 2003), larger amounts of rainfall in the period prior planting wheat will occur. Rainfall will thus come at a time when soils are bare, and at most risk to soil erosion. This could push the negligible amounts of sediment produced by active gully processes in the current stable gullies to relevant levels requiring remedial work. Vegetation was shown to reduce sediment movement significantly, as sediment yield dropped by 91.6% during the study period. The trapping ability of vegetation is however temporary. Sediment is stored when vegetation growth increases with winter rains, but the aggradational ability diminishes once vegetation dies out during summer aridity. These dormant stores can be easily activated and transported downstream by water flow through the gully channels. Remedial work can take the form of planting perennial grass in gully channels, in addition to along ploughed contours. This would ensure a trapping of sediment to be more permanent in nature restabilizing the gully network and reducing the effect that ploughed contours have at delivering sediment to the gully channel by overland flow. Lastly, it is worth mentioning that this was a short-term case study and longer monitoring times should be allocated to these large gully systems in the Swartland to establish the extent of activity and possibly fingerprinting sediment sources. This would lead to a better understanding as it could identify a ratio of sediment yield from different sediment sources. This study also focussed on one gully network and should be expanded to other large gully networks in the region to establish how active these gullies are. Further studies could also investigate sediment yield versus rainfall occurrence to monitor gully erosion on a rainfall event basis instead of monthly such as this study.

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References

Betts, H.D., Trustrum, N.A. & Rose, R.C.D. (2003) Geomorphic changes in a complex gully system measured from sequential digital elevation models, and implications for management. *Earth Surface Processes and Landforms*, **28**, 1043-1058.

Beuselinck, L., Steegen, A., Govers, G., Nachtergaele, J., Takken, I. & Poesen, J. (2000) Characteristics of sediment deposits formed by intense rainfall events in small catchments in the Belgian Loam Belt. *Geomorphology*, **32**, 69-82.

Boardman, J. (2006) Soil erosion science: Reflections on the limitations of current approaches. *Catena*, **68**, 73-86.

Boardman, J., Foster, I.D., Rowntree, K.M., Favis-Mortlock, D.T., Mol, L., Suich, H. & Gaynor, D. (2017) Long-term studies of land degradation in the Sneeuberg uplands, eastern Karoo, South Africa: A synthesis. *Geomorphology*, **285**, 106-120.

Castillo, C. & Gómez, J.A. (2016) A century of gully erosion research: Urgency, complexity and study approaches. *Earth-Science Reviews*, **160**, 300-319.

Chaplot, V., Le Brozec, E.C., Silvera, N. & Valentin, C. (2005) Spatial and temporal assessment of linear erosion in catchments under sloping lands of northern Laos. *Catena*, **63**, 167-184.

Chen, H. & Cai, Q. (2006) Impact of hillslope vegetation restoration on gully erosion induced sediment yield. *Science in China Series D: Earth Sciences*, **49**, 176-192.

Cooke, R.U. & Reeves, R.W. (1976) Arroyos and environmental change in the American South-West. *Oxford*, **328**, 520-57.

DAFF (Department of Agriculture, Forestry and Fisheries) (2017) Wheat production guideline [online]. Available from http://www.daff.gov.za/docs/brochures/prodguidewheat.pdf [Accessed 2 October 2017].

De Baets, S., Poesen, J., Meersmans, J. & Serlet, L. (2011) Cover crops and their erosion-reducing effects during concentrated flow erosion. *Catena*, **85**, 237-244.

De Clercq, W.P., Jovanovic, N. & Fey, M.V. (2010) Land use impacts on salinity in Berg River water. *WRC Report*, No. K5/1503.

Francis, C.F. & Thornes, J.B. (1990) Runoff hydrographs from three Mediterranean vegetation cover types. *Vegetation and erosion. Processes and environments*, 363-384.

Gyssels, G. & Poesen, J. (2003) The importance of plant root characteristics in controlling concentrated flow erosion rates. *Earth Surface Processes and Landforms*, **28**, 371-384.

Hancock, G.R. & Evans, K.G. (2006) Gully position, characteristics and geomorphic thresholds in an undisturbed catchment in northern Australia. *Hydrological Processes*, **20**, 2935-2951.

Kirkby, M.J. & Bracken, L.J. (2009) Gully processes and gully dynamics. *Earth Surface Processes and Landforms*, **34**, 1841-1851.

Le Roux, J.J. & Sumner, P.D. (2012) Factors controlling gully development: comparing continuous and discontinuous gullies. *Land Degradation and Development*, **23**, 440-449.

Mararakanye, N. & Le Roux, J.J. (2012) Gully location mapping at a national scale for South Africa. *South African Geographical Journal*, **94**, 208-218.

Martínez-Casasnovas, J.A., Ramos, M.C. & Poesen, J. (2004) Assessment of sidewall erosion in large gullies using multi-temporal DEMs and logistic regression analysis. *Geomorphology*, **58**, 305-321.

Meadows, M.E. (2003) Soil erosion in the Swartland, Western Cape Province, South Africa: implications of past and present policy and practice. *Environmental Science and Policy*, **6**, 17-28.

Morel, A. (1998) Soil erosion and land degradation in the Swartland and Sandveld, Western Cape Province, South Africa: A re-evaluation (Doctoral dissertation, University of Cape Town).

Nordström, K. (1988) Gully erosion in the Lesotho lowlands. *UNGI Rapport*, **69**, 1-144.

Olivier, G., Helmschrot, J. & De Clercq, W.P. (2016) A GIS based gully classification approach that reflects on origination and process for the Western Cape Province, South Africa. *Zentralblatt Für Geologie und Paläontologie, Teil I*, Jg. 2016, Heft 1, 55-73.

Oostwoud Wijdenes, D.J., Poesen, J., Vandekerckhove, L. & Ghesquiere, M. (2000) Spatial distribution of gully head activity and sediment supply along an ephemeral channel in a Mediterranean environment. *Catena*, **39**, 147-167.

Poesen, J.W. & Hooke, J.M. (1997) Erosion, flooding and channel management in Mediterranean environments of southern Europe. *Progress in Physical Geography*, **21**, 157-199.

Poesen, J., Nachtergaele, J., Verstraeten, G. & Valentin, C. (2003) Gully erosion and environmental change: importance and research needs. *Catena*, **50**, 91-133.

Poesen, J., Vandekerckhove, L., Nachtergaele, J., Oostwoud Wijdenes, D., Verstraeten, G. & van Wesemael, B. (2002) Gully erosion in dryland environments. *Dryland rivers: hydrology and geomorphology of semi-arid channels.* (ed. by Bull, L.J. & Kirkby, M.J.), 229-262. Wiley, Chichester, UK.

Poesen, J., Vandekerckhove, L., Nachtergaele, J., Oostwoud Wijdenes, D., Verstraeten, G., & van Wesemael, B. (2002) Gully erosion in dryland environments. *Bull, LJ, Kirkby, MJ (Eds.), Dryland rivers: hydrology and geomorphology of semi-arid channels.*

Rey, F. (2003) Influence of vegetation distribution on sediment yield in forested marly gullies. *Catena*, **50**, 549-562.

Rowntree, K.M. (2014) Reprint of: The evil of sluits: A re-assessment of soil erosion in the Karoo of South Africa as portrayed in century-old sources. *Journal of Environmental Management*, **138**, 67-74.

Sidorchuk, A. (1999) Dynamic and static models of gully erosion. *Catena*, **37**, 401-414.

Steudel, T., Bugan, R., Kipka, H., Pfennig, B., Finckh, M., de Clercq, W., Flügel, W.A. & Helmschrot, J. (2015) Implementing contour bank farming practices into the J2000 model to improve hydrological and erosion modelling in semi-arid Western Cape Province of South Africa. *Hydrology Research*, **46**, 192-211.

Talbot, W.J. (1947) Swartland and Sandveld: A survey of land utilization and soil erosion in the western lowland of the Cape Province. *Oxford University Press*.

Valentin, C., Poesen, J. & Li, Y. (2005) Gully erosion: impacts, factors and control. *Catena*, **63**, 132-153.

References [CrossRef]

Betts, H.D., Trustrum, N.A. & Rose, R.C.D. (2003) Geomorphic changes in a complex gully system measured from sequential digital elevation models, and implications for management. *Earth Surface Processes and Landforms*, **28**, 1043-1058. CrossRef

Beuselinck, L., Steegen, A., Govers, G., Nachtergaele, J., Takken, I. & Poesen, J. (2000) Characteristics of sediment deposits formed by intense rainfall events in small catchments in the Belgian Loam Belt. *Geomorphology*, **32**, 69-82. CrossRef

Boardman, J. (2006) Soil erosion science: Reflections on the limitations of current approaches. *Catena*, **68**, 73-86. CrossRef

Boardman, J., Foster, I.D., Rowntree, K.M., Favis-Mortlock, D.T., Mol, L., Suich, H. & Gaynor, D. (2017) Long-term studies of land degradation in the Sneeuberg uplands, eastern Karoo, South Africa: A synthesis. *Geomorphology*, **285**, 106-120. CrossRef

Castillo, C. & Gómez, J.A. (2016) A century of gully erosion research: Urgency, complexity and study approaches. *Earth-Science Reviews*, **160**, 300-319. CrossRef

Chaplot, V., Le Brozec, E.C., Silvera, N. & Valentin, C. (2005) Spatial and temporal assessment of linear erosion in catchments under sloping lands of northern Laos. *Catena*, **63**, 167-184. CrossRef

Chen, H. & Cai, Q. (2006) Impact of hillslope vegetation restoration on gully erosion induced sediment yield. *Science in China Series D: Earth Sciences*, **49**, 176-192. CrossRef

Cooke, R.U. & Reeves, R.W. (1976) Arroyos and environmental change in the American South-West. *Oxford*, **328**, 520-57.

DAFF (Department of Agriculture, Forestry and Fisheries) (2017) Wheat production guideline [online]. Available from http://www.daff.gov.za/docs/brochures/prodguidewheat.pdf [Accessed 2 October 2017].

De Baets, S., Poesen, J., Meersmans, J. & Serlet, L. (2011) Cover crops and their erosion-reducing effects during concentrated flow erosion. *Catena*, **85**, 237-244. CrossRef

De Clercq, W.P., Jovanovic, N. & Fey, M.V. (2010) Land use impacts on salinity in Berg River water. *WRC Report*, No. K5/1503.

Francis, C.F. & Thornes, J.B. (1990) Runoff hydrographs from three Mediterranean vegetation cover types. *Vegetation and erosion. Processes and environments*, 363-384.

Gyssels, G. & Poesen, J. (2003) The importance of plant root characteristics in controlling concentrated flow erosion rates. *Earth Surface Processes and Landforms*, **28**, 371-384. CrossRef

Hancock, G.R. & Evans, K.G. (2006) Gully position, characteristics and geomorphic thresholds in an undisturbed catchment in northern Australia. *Hydrological Processes*, **20**, 2935-2951. CrossRef

Kirkby, M.J. & Bracken, L.J. (2009) Gully processes and gully dynamics. *Earth Surface Processes and Landforms*, **34**, 1841-1851. CrossRef

Le Roux, J.J. & Sumner, P.D. (2012) Factors controlling gully development: comparing continuous and discontinuous gullies. *Land Degradation and Development*, **23**, 440-449. CrossRef

Mararakanye, N. & Le Roux, J.J. (2012) Gully location mapping at a national scale for South Africa. *South African Geographical Journal*, **94**, 208-218. CrossRef

Martínez-Casasnovas, J.A., Ramos, M.C. & Poesen, J. (2004) Assessment of sidewall erosion in large gullies using multi-temporal DEMs and logistic regression analysis. *Geomorphology*, **58**, 305-321. CrossRef

Meadows, M.E. (2003) Soil erosion in the Swartland, Western Cape Province, South Africa: implications of past and present policy and practice. *Environmental Science and Policy*, **6**, 17-28. CrossRef

Morel, A. (1998) Soil erosion and land degradation in the Swartland and Sandveld, Western Cape Province, South Africa: A re-evaluation (Doctoral dissertation, University of Cape Town).

Nordström, K. (1988) Gully erosion in the Lesotho lowlands. *UNGI Rapport*, **69**, 1-144.

Olivier, G., Helmschrot, J. & De Clercq, W.P. (2016) A GIS based gully classification approach that reflects on origination and process for the Western Cape Province, South Africa. *Zentralblatt Für Geologie und Paläontologie, Teil I*, Jg. 2016, Heft 1, 55-73.

Oostwoud Wijdenes, D.J., Poesen, J., Vandekerckhove, L. & Ghesquiere, M. (2000) Spatial distribution of gully head activity and sediment supply along an ephemeral channel in a Mediterranean environment. *Catena*, **39**, 147-167. CrossRef

Poesen, J.W. & Hooke, J.M. (1997) Erosion, flooding and channel management in Mediterranean environments of southern Europe. *Progress in Physical Geography*, **21**, 157-199. CrossRef

Poesen, J., Nachtergaele, J., Verstraeten, G. & Valentin, C. (2003) Gully erosion and environmental change: importance and research needs. *Catena*, **50**, 91-133. CrossRef

Poesen, J., Vandekerckhove, L., Nachtergaele, J., Oostwoud Wijdenes, D., Verstraeten, G. & van Wesemael, B. (2002) Gully erosion in dryland environments. *Dryland rivers: hydrology and geomorphology of semi-arid channels.* (ed. by Bull, L.J. & Kirkby, M.J.), 229-262. Wiley, Chichester, UK.

Poesen, J., Vandekerckhove, L., Nachtergaele, J., Oostwoud Wijdenes, D., Verstraeten, G., & van Wesemael, B. (2002) Gully erosion in dryland environments. *Bull, LJ, Kirkby, MJ (Eds.), Dryland rivers: hydrology and geomorphology of semi-arid channels.*

Rey, F. (2003) Influence of vegetation distribution on sediment yield in forested marly gullies. *Catena*, **50**, 549-562. CrossRef

Rowntree, K.M. (2014) Reprint of: The evil of sluits: A re-assessment of soil erosion in the Karoo of South Africa as portrayed in century-old sources. *Journal of Environmental Management*, **138**, 67-74. CrossRef

Sidorchuk, A. (1999) Dynamic and static models of gully erosion. *Catena*, **37**, 401-414. CrossRef

Steudel, T., Bugan, R., Kipka, H., Pfennig, B., Finckh, M., de Clercq, W., Flügel, W.A. & Helmschrot, J. (2015) Implementing contour bank farming practices into the J2000 model to improve hydrological and erosion modelling in semi-arid Western Cape Province of South Africa. *Hydrology Research*, **46**, 192-211. CrossRef

Talbot, W.J. (1947) Swartland and Sandveld: A survey of land utilization and soil erosion in the western lowland of the Cape Province. *Oxford University Press*.

Valentin, C., Poesen, J. & Li, Y. (2005) Gully erosion: impacts, factors and control. *Catena*, **63**, 132-153. CrossRef

Impact of mining on the environment and water resources in northeastern Angola

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Abstract: Mining, and particularly diamond exploitation, is one of the most ancient human economic activities and even today plays a crucial role in the economy of many countries. Our study aimed to inventory and map mining activities in the northeastern provinces of Angola (Lunda Norte and Lunda Sul) to enable the subsequent assessment of their impact on the natural environment and on water resources. To achieve this aim, we carried out several field campaigns. Various effects on the environment have been observed, ranging from visual impact to deforestation, soil depletion, and changes in topography. Water resources are the most affected part of the ecosystem, resulting in pollution of lakes and rivers, changes in river courses, silting of streams, and the dry-up of some watercourses. As a whole, our observations show that the effects of mining activities on water pollution in rivers impact large parts of the northeastern provinces of Angola and reach the border areas of the inner Congo Basin.

Resumo: A mineração, especialmente a exploração de diamantes, é uma das actividades económicas antigas dos homens e, até hoje, desempenha um papel crucial na economia de muitos países. Este estudo teve como objectivo efectuar um inventário e o mapeamento das actividades mineiras nas províncias do Nordeste de Angola de Lunda Norte e Lunda Sul, para uma posterior avaliação do seu impacto no meio natural e nos recursos hídricos. Para atingir esse objectivo, foram realizadas várias campanhas de campo. Observaram-se vários tipos de impactos no ambiente, desde impactos visuais e desmatamento, depleção do solo e mudanças na topografia. Os recursos hídricos são a parte mais afectada do ecossistema, resultando em poluição de lagos e rios, mudanças nos cursos de rios, assoreamento de riachos e extinção de alguns cursos de água. De um modo geral, as observações mostram que os efeitos das actividades de mineração sobre a poluição das águas dos rios cobrem quase todas as partes das províncias do Nordeste de Angola, e atingem as áreas fronteiriças da bacia interna do Congo.

Introduction

Mining can take a variety of forms, such as quarrying, dredging, drilling of wells, and other forms of surface exploitation, but also includes subsurface activities carried out in underground mining galleries. According to Craig et al. (2007), extractive activities can lead to a number of environmental problems, among which those related to sterile (sediment) discharges during the clearing and extraction processes and to wastewater discharges resulting from extraction treatments should be particularly highlighted. There is, of course, a set of standardized measures and procedures for the proper conduct of mining activities. However, the mode of exploitation depends greatly on the characteristics of the minerals and the interests and responsibility taken by the explorer.

The extraction of diamonds in the northeastern Angolan provinces of Lunda Norte and Lunda Sul dates back to the first decade of the 1900s, thanks to the discovery of large deposits of diamond, which are still being exploited there today. The deposition of phanerozoic sedimentary sequences resting discontinously on previously eroded surfaces (Pereira et al., 2003) and the subsequent breakup of Gondwana during the Jurassic to Cretaceous, between 190 and 60 Ma (e.g., Jelsma et al., 2004), caused the development of basins that are associated with deep fault systems in Angola. These fault systems facilitated the intrusion of alkaline, carbonatic, and kimberlite magmas (Pereira et al., 2003) and permitted the mineralization of diamonds in the region, primarily in the eastern parts of Angola.

As one of the traditional economic activities in the Lunda provinces, diamond mining plays a crucial role in the region's economy and supports many livelihoods. Activity is dispersed over large areas of the northeastern region following along kimberlitic rocks and fluvial sediments. However, information is lacking on the degree of environmental transformation caused by the impacts of such anthropic mining activity. Therefore, the main focus of this study is to present an environmental diagnosis of the mining activities carried out in the northeastern provinces of Angola, including a brief summary of the mining procedures and their implications for the natural environment.

Methods

Between 2014 and 2016, we conducted several field campaigns covering Angola's Lunda Norte and Lunda Sul provinces in order to carry out an inventory of mining-related land use activities and their respective characterisations. During each campaign, we visited some of the large enterprises that constitute the main actors of mining in the region. The campaigns took place in both the dry and rainy seasons. We applied qualitative methods such as observation, photographic documentation, and comparison of main features to describe the location, type, and characteristics of the activities carried out and to observe the extant sterile and waste treatments, e.g. the mineral extraction areas, tailings, sterile deposits, stockpiles, camps and warehouses, and treatment areas. To estimate the loss of vegetation, surrounding natural land was compared with exploited areas, which allows assessment of mining's effects at the landscape level.

The conditions for the treatment and disposal of mine wastewater into rivers or retention basins, river deviations, sediment inputs, and silting of streams were recorded. We also assessed the state of affected river sections and of undisturbed river sections under natural conditions, with emphasis on the modification of river margins, turbidity of the water, silting, and sediment loads.

In the next step, we analyzed the acquired data, conducted photograph and aerial image interpretation, and integrated the results in thematic maps. Change detection was done by visual image interpretation. In some cases, this involved comparing different places with different land uses; in other cases, we analysed time series of mining hotspots in order to detect changes within the systems.

To quantify impacts at landscape scale, we studied the land use evolution in the Cuango municipality by comparing the area occupied by mining, urban settlements, and undisturbed land between 2005 to 2015. Our methodology involved a land-use classification of Landsat images, based on a mixed-scale approach using descriptive statistics and GIS tools, which allowed us to calculate the land cover maps and the occupied area for each of the analysed land use types and their respective percentage of change.

In order to broaden the spectrum of information available for study, interviews were conducted with members of the local population, exploration company technicians, artisanal miners, local authorities at different levels, and stakeholders from related national authorities (e.g., water, geology, mining). These populations were asked about the benefits of the mining operations for the communities, their aspirations, and about the inconveniences caused by mining. For mining technicians, managers, and prospectors, the focus of the interview was on work procedures and environmental responsibility. For government authorities, the most frequently addressed issues were compliance with mining regulations; management of possible conflicts between stakeholders, especially between local populations and mining companies; and concerns regarding local water supplies and the implications caused by the use of untreated water from rivers affected by mining operations.

Results

Mineralisation and forms of mineral exploitation

The diamond reserves in the Lunda provinces can be found as kimberlitic rocks and as alluvial deposits. Kimberlites are primary mineralisation which occur in the depths and reach the surface; alluvial deposits are secondary mineralisation, occurring as a result of weathering and erosion of the superficial part of the kimberlite—their material accumulates in the most superficial layers. Depending upon the type of mineralisation, the ore can be explored using different techniques. In both cases, it is necessary to remove huge quantities of sterile materials (e.g., thick layers of gangue) before reaching the ore layer (gravel). This implies occupying large areas of land for the deposition of waste rock, as well as other spaces required for the treatment of the ore and the tailings for the washing water produced during the operational processes.

Mining activity in the Lunda provinces is carried out at three scales: an industrial scale, which operates large-scale mining projects; a semi-industrial scale in which newly created mining cooperatives operate; and finally, an artisanal scale, the so-called 'garimpo'.

Industrial mining exploitation

Industrial diamond mining is carried out by large enterprises employing heavy and varied machinery; these efforts occupy large tracts of land. For both types of deposits, industrial-scale extraction is done using open pit mines. In the case of kimberlites, the pits can reach depths of more than 90 m, whereas with alluvial deposits, the diamond can be found in more superficial gravel layers. Industrial

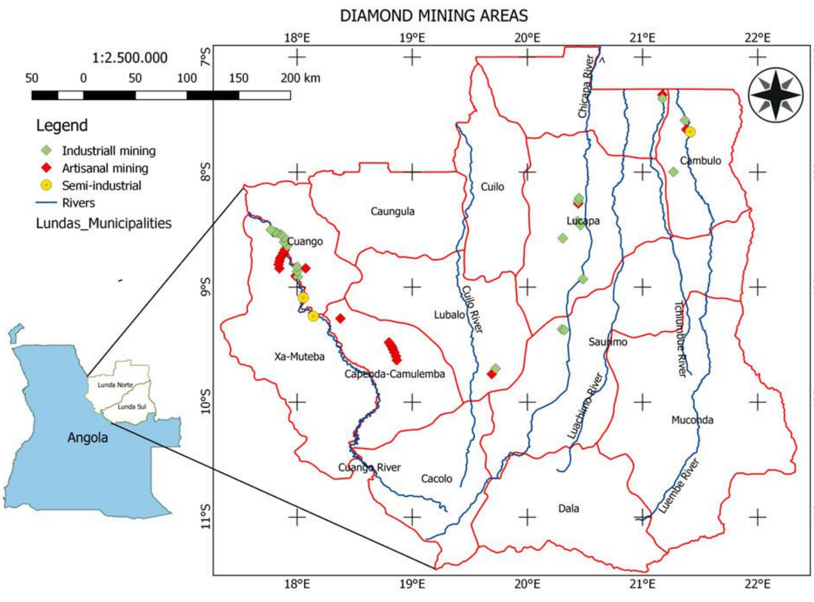

Figure 1: Distribution of mining activities in the Lunda provinces.

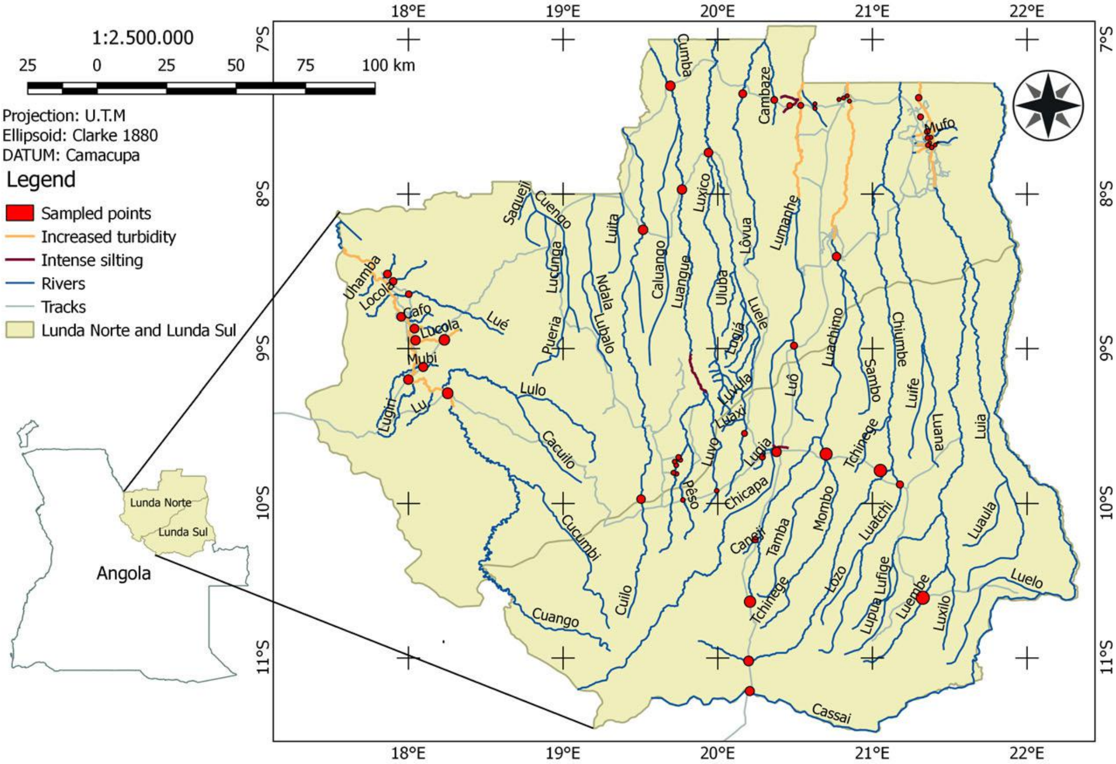

Figure 2: Hydrographic network showing affected rivers (turbidity and silting) (modified from Esri, HERE, Delorme, Intermap).

mining uses trucks with up to a 20 t payload to move huge quantities of excavated material and consumes high volumes of water for pretreatment and gravel washing operations. The used washing and mining waters are a cause of a great concern, as they have to pass through retention basins and must be treated before their final disposal in rivers. Most of the mining projects we visited, however, did not have appropriate tailings, so the waste water was poured directly into the rivers. One diamond mining project of medium size, exploring a kimberlite in Lunda Norte, moves about 123 000 m^3 of waste rock and 75 000 m^3 of kimberlite per month and consumes about 375 m^3 of water per hour.

When large mining concerns exploit alluvial deposits on active riverbeds, they frequently build dikes and force the rivers to deviate. At the start of exploitation, most of mining projects deviate the river courses over a large distance; however, in some cases, they remove gravel from the riverbed by dredging with powerful electric pumps.

Semi-industrial exploitation

Associations of small mining entrepreneurs, using medium and small equipment, work at the scale of semi-industrial exploitation. This type of exploitation is usually conducted in alluviums using mechanized equipment. Installations at this level are smaller than in industrial mining, with lower volumes of earth moved and less water used for the washing process. The latter is normally done by hand directly in the streams, employing a local work force without specialisation.

Artisanal mining: Garimpo

Artisanal mining, the so called 'garimpo', is widely scattered across almost the entire territory of both Lunda provinces, mainly in the municipalities of Cuango, Cambulo, and Lucapa, as well as in the vicinity of the large industrial explorations. Generally, it is carried out by the local population, individually or in small groups. In the artisanal type of exploitation, the miners make their explorations in alluvial sediments and in the riverbeds. Dismantling and extraction are done using simple tools such as hoes, shovels, and picks. The transport of the gravel is done manually, in baskets, bags, or handcarts and its treatment (washing) is carried out with sieves and batts, again manually. This manual washing process is preferably done on the banks and beds of the rivers and lakes.

In all three types of mining exploitation, we detected procedures which affected the environment and particularly the available water resources, although in different dimensions:

- Dismantling and extraction of the alluvial deposits encourages deforestation of large swaths of land, leading to the decrease or total destruction of land cover; after abandonment, the exploited areas are not properly restored.

- Washing gravel in riverbeds and expelling wastewater into rivers leads to siltation, enhances turbidity, and increases the suspended material content of the water. Figure 2 shows the hydrographic network of the region and the river sections most affected by anthropic mining activities.

Other notable impacts concern the deviation and cutting-off of watercourses; in some cases, the affected streams are completely silted, to the point that they lose their normal flow rates. Field observations confirmed the extinction of some small rivers due to silting, excavations in their beds, and frequent deviation of their courses by mining activities.

Figure 3: (a) industrial mining; (b) artisanal mining; (c) river deviation and artisanal mining along a riverbed; (d) silted river; (e) increased turbidity in river water; (f) consumption of turbid and untreated water.

Table 1 shows the land use evolution of a part of the Cuango municipality from 2005 to 2015, with respect to the areas occupied by vegetation, urbanisation, and mining activities. Notably, the increase in areas affected by mining is still larger in other municipalities (e.g. Cambulo), which implies a larger loss of natural vegetation cover there.

Discussion

Industrial mining of diamonds is a long-standing practice, and in the northeastern provinces of Angola, the exploitation phase of the major mining projects is estimated to last more than 50 years; the oldest mining projects in the Lunda provinces are still active. Due to the procedures used by these industries and because of their persistence, dimensions, and long duration, the implications of industrial mining activities for the environment and particularly for water resources are much more significant than those of artisanal short-term exploitations.

Most of the mining activities identified in our study area have a preferential exploitation space along banks and riverbeds; at the least, they cross some watercourses. This is the case both in alluvial and kimberlite exploitation schemes.

So far, all industrial mining projects in the Lunda provinces (in both kimberlites and alluvial deposits) have been carried out in open pit mines, which significantly transform the surface structure of the landscape and have a lasting impact on soils, vegetation, and watercourses. This increases the vulnerability of these components of the ecosystem, both during the exploitation phase as well as after the end of mining activities. The effects of these activities are visible in all areas of exploitation throughout the Lundas.

The decrease in vegetation cover, the destruction of ecosystems, and the abandonment of exploited areas without proper restoration are some of the most relevant observed effects of mining in northeastern Angola. Because banks and beds of watercourses, streams, and lakes are the preferred sites for diamond extraction as well as for the gravel washing, mining leads to increased turbidity and increased loads of suspended materials in the water, making it dangerous for human consumption. Unfortunately, most of the industrial mining exploitation projects we visited do not have tailings; they expel the mining water and derivative effluents from their operations directly into the rivers without applying wastewater treatments or taking other appropriate precautions. Figures 1 and 2 clearly show that the river sections most affected by turbidity and silting coincide with the distribution of the main mining areas. Industrial mining affects watercourses to a much higher degree and reaches farther downriver into greater streams than artisanal mining, the effects of which are somewhat restrained to smaller rivers and to shorter river sections. Meanwhile, in non-mining and sparsely populated areas, the rivers still exhibit good water quality.

Our landscape analysis revealed that the areas of mining exploitation, including those that have been abandoned, demonstrate a notable long-term reduction in vegetation cover. The area currently occupied by mining and urbanisation is increasing while natural areas continue to decline. In the region, the area used for mining has more than quadrupled within the last 10 years (see Tab. 1), demonstrating how mining activity is increasing dramatically. If this development continues unabated, the effects on water pollution will increase seriously over the next

Table 1: Land cover change in the Cuango municipality from 2005 to 2015.

Description	Area (km²)	Area (km²)	Δ	%	%	Δ
Year	2005	2015	(km²)	2005	2015	%
Total area	1 108.2	1 108.2	0	100%	100%	0
Natural vegetation	1 095.0	1 078.8	-16.1	98.8	97.4	-1.5
Urban settlements	9.9	15.1	5.2	0.9	1.4	0.5
Mining area	3.4	14.3	10.9	0.3	1.3	0.9

several years and the extent of the rivers affected by turbidity and silting could increase proportionately dramatically (see Fig. 2 and 3).

Conclusion

In general, environmental degradation from mining in northeastern Angola consists of reduction of vegetation cover, environmental degradation due to the abandonment of exploited areas, a lack of restoration after the end of exploitation in an area, the dismantling of large areas by mining activities, a decrease in the water quality of rivers and lakes, and the silting and extinction of streams. Mining activities in the Lundas currently significantly impact water resources; more precautions are necessary to reduce adverse effects on the environment. The effects of river water pollution affect large parts of northeastern Angola and reach the transboundary areas of the Congo Basin. These effects are more pronounced in areas of intense mining activities, as illustrated in our maps of the region (see Fig. 1 and 2).The local population is affected by these activities due to the reduction of sources of clean (potable) water for consumption, particularly because some parts of important rivers such as the Luangue, Luembe, Luachimo, Cuango, Chicapa, Luxilo, Nzagi, and Mucunene are affected, exhibiting a high turbidity. However, due to the lack of alternative sources of potable water, the population has no other options than to consume contaminated water that has not undergone previous treatment. For this reason, we recommend that the ministry of mineral resources and petroleum enforce the use of good practices in the mining sector to prevent the dumping of mine waters in conditions little suitable and consequent pollution of the environment

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References

Barbosa, O. (1991) Diamante no Brasil: Histórico, ocorrências, prospecção e lavra. CPRM, Rio de Janeiro.

CETEM. (2005) Rochas e minerais industriais. CETEM, Rio de Janeiro.

Craig, J.R., Vaughan, D.J. & Skinner J.B. (2006) Recursos de la Tierra. Origem, uso e impacto.

FAO. (2005) Land cover classification system. Environment and natural resources series. FAO, Rome.

Jelsma, H.A., de Wit, M.J., Thiart, C., Dirkes, P.H.G.M., Basson, I.J. & Anckar, E. (2004) Preferential distribution along transcontinental corridors of kimberlites and related rocks of southern Africa. *South African Journal of Geology*, **107**, 301–324.

Pereira, E., Rodrigues, J. & Reis, B. – Synopsis of Lunda geology, NE Angola: implications for diamond exploration. In: Comunicações do Instituto Geológico e Mineiro, 2003, Tomo 90, p. 189–212.

Drought sensitivity in the Cuvelai Basin: empirical analysis of seasonal water and food consumption patterns

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Abstract: The population in Sub-Saharan Africa is regularly affected by droughts, such as those recently triggered by El Niño. Rural smallholders in semi-arid environments such as the transnational Cuvelai Basin in southern Angola and northern Namibia directly depend on local blue and green water availability and are therefore at risk of drought. This study builds on local knowledge of seasonal water and food consumption patterns to estimate household drought sensitivity. An empirical survey was conducted with 461 households to (1) determine the reliability of water and food source types under dry conditions, (2) estimate consumption dependencies, and (3) contribute to drought risk assessments. The consumption patterns reveal differences in the reliability of source types. In particular, traditional types are used extensively during the rainy season but become unavailable during the dry season. Households with a strong dependence on these types are particularly sensitive to drought. This is true for rural areas, notably in Angola, where reliable water and food infrastructures are less available. This methodology can be implemented in conventional surveys to continuously monitor drought sensitivity conditions on the household level.

Resumo: A população da África Subsariana é regularmente afectada pela seca, recentemente desencadeada pelo El-Niño. Os pequenos agricultores rurais em ambientes semiáridos dependem directamente da disponibilidade local de água azul e verde e estão, por isso, em risco de seca, tal como se verifica na bacia transnacional de Cuvelai, no Sul de Angola e Norte da Namíbia. Este estudo baseia-se no conhecimento local da água sazonal e dos padrões de consumo de alimentos, de modo a estimar a sensibilidade domiciliar à seca. Foi realizado um estudo empírico com 461 famílias para (i) determinar a fiabilidade dos tipos de fontes de água e alimentos sob condições de seca, (ii) estimar as dependências de consumo e (iii) contribuir para as avaliações do risco de seca. Os padrões de consumo revelam diferenças na fiabilidade dos tipos de fontes. Em especial, os tipos tradicionais são usados extensivamente durante a época das chuvas, mas ficam indisponíveis na época seca. As famílias com uma forte dependência dos respectivos tipos são particularmente sensíveis à seca. Isto é verdade para áreas rurais, especialmente em Angola, onde há menor disponibilidade de infraestruturas de água e alimentos. Esta metodologia pode ser implementada em estudos convencionais para continuamente monitorizar as condições de sensibilidade à seca ao nível doméstico.

1. Introduction

Droughts are a critical threat throughout Sub-Saharan Africa (UNISDR, 2012). People who inhabit particular semi-arid environments adapted to the conditions centuries ago (Ehret, 2001). They developed adequate strategies to utilize the limited blue and green water resources (Falkenmark & Rockström, 2006; Freire-González et al., 2017) in an efficient way to meet their needs for domestic water and food consumption (Diao et al., 2010; Collier & Dercon, 2014). However, enhanced population growth, economic development, and urbanization in conjunction with a changing climate and limited coping capacities (Thornton & Herrero, 2015) alter the way societies interact with their environment and create challenges not experienced in the past. Consequently, severe and prolonged droughts, such as those recently aggravated by El Niño in large parts of Sub-Saharan Africa (Baudoin et al., 2017; Smith & Ubilava, 2017), are occurring more frequently and have a stronger impact.

Droughts play a major role in the transnational Cuvelai Basin in southern Angola and northern Namibia (Luetkemeier et al., 2017). The majority of the population is strongly connected to the hydroclimatic conditions to sustain their livelihoods, since subsistence agriculture and traditional water supply systems remain dominant (Luetkemeier & Liehr, 2015).

As commonly found in developing countries, food and water consumption follow complex patterns (Nauges, 2008; Fiedler, 2013). Households utilize a broad range of source types (e.g., shallow wells and tap water, self-collected wild food and supermarkets), depending on determinants such as seasonal availability and quality aspects, infrastructural endowment, and price and distance. Though this consumption strategy reduces the risk of individual source failures, the traditional food and water source types respond quickly to drought-induced blue and green water scarcity. As a result, households that strongly depend on unreliable sources are highly sensitive to drought events and suffer second-order effects if they are not able to switch to more reliable sources (Luetkemeier & Liehr, 2015).

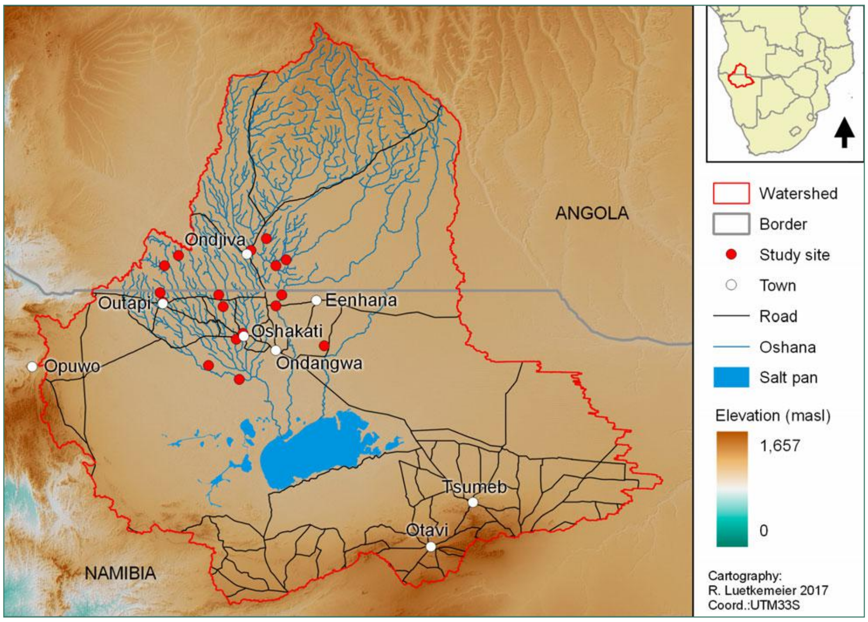

Figure 1: Cuvelai-Basin, indicating the locations of the empirical household survey in southern Angola and northern Namibia.

Methodologically, the assessment of household water demand in developing countries remains a challenge because of complex patterns and multiple influencing factors. Household surveys are a commonly used method to assess the water quantities withdrawn and the purposes water is used for (Gleick, 1996; Inocencio et al., 1999; Nauges, 2008; Dagnew, 2012). Similarly, food consumption, especially nutritional content, is typically assessed via interviews. In these surveys, methods such as 24-hour recall and observed-weighed food records are preferred but require larger assessment efforts (Fiedler, 2013). The household economy approach (HEA) instead takes a pragmatic perspective and assesses the range and relative importance of food sources by converting available dietary energy into monetary terms (Seaman et al., 2014). Conventional household surveys deliver less detailed information on water and food consumption since they neglect the underlying complexity by focusing on the main sources utilized (NSA, 2013; INE, 2016). Recently, Elliott et al. (2017) made a strong case for considering multiple water sources when assessing consumption patterns. They found that detailed assessments in this regard provide valuable information to determine the adaptive capacities of communities in the Pacific Island countries, particularly with respect to climate change adaptation (Elliott et al., 2017). This study takes up these methodological developments and expands the focus to include food consumption patterns as well.

The more in-depth consideration of water utilization in northern Namibia is particularly relevant because of the increasing share of unsafe water sources in recent years. The utilization of safe water sources (WHO & UNICEF, 2017) declined in Namibia from 2001 to 2011, which is true for the northern regions of Ohangwena (78% to 56%), Oshikoto (88% to 70%), Oshana (93% to 84%), and Omusati (83% to 52%) (NSA, 2013). Research is needed to uncover the underlying complexity of consumption patterns. Conventional survey techniques that assess the main water and food source types are not suitable for this purpose and hide valuable seasonal and structural information.

Building on qualitative insights into drought risk in the Cuvelai Basin, methodological opportunities and shortcomings, and development challenges in Namibia and Angola, this paper seeks to determine a household's sensitivity to drought by assessing seasonal water and food consumption patterns. This supports the integrated Household Drought Risk Index (HDRI) as a holistic drought risk assessment tool (Luetkemeier, ISOE, unpubl.) and presents a transferable methodology to be included in conventional census survey techniques for continuous drought sensitivity monitoring.

Specifically, this study develops and applies an empirical assessment tool to make contributions to:

- determine unreliable water and food source types under dry conditions,
- identify households that strongly depend on unreliable water and food source types,
- use those data to estimate drought sensitivities on the household level and thereby contribute to the household drought risk assessment, and
- present methodological advancements to improve conventional survey techniques.

This paper first introduces the conceptual approach of risk research and the study area in northern Namibia and southern Angola. Subsequently, the key methodological techniques of the empirical survey are presented alongside the analytical steps to draw conclusions on source reliability and consumption dependence. The results provide insights into drought sensitivity estimates for the Angolan and the Namibian populations as well as people living in rural and urban settings. The discussion and the conclusion will reflect on the results with special emphasis on the method's potential to improve conventional survey techniques.

Methods

The following sections provide a brief description of the study's methodological setup. First, the conceptual approach is presented, in which drought sensitivity is incorporated into the concept of risk and vulnerability. Second, the study area is introduced by highlighting the most important geographical features. Third, the design of the household survey is presented, followed by a description of the analytical procedure to analyse and process the data.

Conceptual approach

Droughts are regarded as a critical hazard in the study area. For the purpose of assessing the impact of drought hazard on the local population, a holistic conceptual approach is adapted in which risk is a function of hazard and vulnerability (Wisner et al., 2003; Cardona et al., 2012). While drought is regarded as the hazard that can be characterized by frequency of occurrence, severity, and duration (Luetkemeier et al., 2017), vulnerability incorporates sensitivity and coping capacity to characterize the ability of a household to handle a drought situation. Within this conceptual framing, this study specifically focuses on the sensitivity aspect to make a contribution to the integrated Household Drought Risk Index (HDRI) (Luetkemeier, ISOE, unpubl.).

Study area

The Cuvelai Basin is located in southern Angola and northern Namibia, covering a total area of about 172,000 km2 with a population of about 1.7 million people (NSA, 2013; INE, 2016). From a hydro-climatic perspective, the watershed is a complex system with a strong seasonal variation of precipitation and associated surface and subsurface water availability. The ephemeral streams, locally known as iishana (sing. oshana), are a key characteristic of the endorheic watershed, carrying water during the rainy season and regularly leading to flood events (Mendelsohn & Weber, 2011). The rainfall variability over time is pronounced, resulting in changes in soil moisture and vegetation conditions (Luetkemeier et al., 2017).

The socio-economic setting of the area is predominantly characterized by a rural subsistence economy based on rain-fed farming and extensive livestock management. Despite these traditional structures, urbanization has gained momentum throughout the past decades, partly changing peoples' lifestyles. This is particularly true for the Namibian side of the basin, as it is better endowed with modern infrastructure such as a road network, electricity, and a tap water system. The Angolan part is however, generally less developed, providing these systems only in major urban agglomerations (Mendelsohn & Weber, 2011).

Structured household survey

The primary assessment tool is a structured questionnaire that is divided into two major parts. Part A assesses water and food consumption patterns on a seasonal basis, while part B focuses on the coping capacities of households. Relevant to this study is part A of the survey, while the results of part B are incorporated into the HDRI assessment (Luetkemeier, 2015, Luetkemeier, ISOE, unpubl.).

The questionnaire was carried out in northern Namibia with a total of 310 households and in southern Angola with about 151 households. The entire sample of 461 households was selected based on a three-stage procedure. In the first stage, 10 administrative areas were randomly selected using the probability proportional to size (PPS) approach (Lavrakas, 2008). Herein, administrative units with a higher population receive a higher probability of being selected, resulting in a more equal probability that each household will be part of the sample. In the second sampling stage, two villages were selected in each of the chosen administrative units in close collaboration with local experts. They were encouraged to choose representative settlements (urban and rural), taking aspects such as water infrastructure endowment, livelihood settings, and accessibility into account. In the third stage, the trained interviewers followed a random walk approach and tried to interview as many households as possible from the selected villages. Figure 1 depicts the study sites in the centre of the Cuvelai Basin, covering the area where most of the population lives.

Demand for water and food

The overall demand for water and food on the household level is regarded as essential for depicting sensitivity to drought. Though the capacity to cope with drought situations is likely to be higher in a household with more members (e.g., more workforce), the challenge of acquiring adequate quantities of high-quality water and food is more acute than in a smaller household. Hence, larger households are regarded as being more sensitive to drought than smaller households. This assumption was incorporated by estimating the demand for water and food from the number, age, and gender of the household members. While in the case of water consumption a nonlinear degressive relationship was assumed (Arouna & Dabbert, 2009), food consumption per household member was adapted to the age- and gender-specific dietary energy requirements (Institute of Medicine, 2005).

Consumption quantities

Beside the water and food quantities that a household requires, it is important to characterize the predisposition of the households' consumption patterns to drought. This predisposition is composed of two parameters, (1) relative water and food quantity withdrawn per source type and (2) source type reliability. To assess data on both parameters, a pretested structured questionnaire was designed to assess the number and type of water and food sources a household utilizes as well as the relative quantities that are withdrawn from these source types (Fig. 2).

As a first step, the household head or his/her partner was supposed to select the water and food source types they utilize in an average rainy and an average dry season. If the respondents mentioned more than one source type, they were asked subsequently to rank the selected source types according to the amount of water or food withdrawn. In this regard, higher quantities are withdrawn from a source type ranked 2nd than from a source type ranked 4th, for instance. This assessment and the evaluation of source types was conducted for the rainy and the dry seasons in order to uncover changes that serve as an indication of a source type's reliability under dry conditions. Both the water and food source types included a range of traditional and modern types that were assessed in a qualitative research phase (Luetkemeier & Liehr, 2015) and the pretest.

The rankings constitute a household's expression of how much water and food are withdrawn from a specific source type during the dry and the rainy seasons to meet household demand. Thus, the responses are aggregated statements that incorporate a complex decision-making and evaluation process. Therein, influencing factors such as price, distance, and quality aspects are already incorporated by the respondents, but this complexity is hidden in the ranking scheme.

While the assessment of absolute values for water and food quantities via questionnaires is time-consuming and prone to misinterpretation, the assigned rankings had to be transformed into relative estimates of water and food quantities. Herein, it was assumed that the source types mentioned meet 100% of the entire household demand and that the rankings provide insight into the relative quantities obtained.

Source type reliability

Now that each household has provided information on how much water or food it withdraws from a particular source type, the patterns can be compared between the two seasons. If a difference between the seasons is apparent, conclusions can be drawn on the reliability of specific source types under dry conditions. As an example, a household might utilize three water source types in the rainy season: (1) shallow well, (2) improved deep well, and (3) public tap. In the dry season however, the pattern might switches to (1) public tap and (2) improved deep well. The shallow well was abandoned because of either quantity or quality constraints, while the public tap is now the primary source type.

From this seasonal consumption change it is possible to draw conclusions on reliability, assuming that during a drought period, dry-season conditions prevail and are even more intense. Hence, analysing the sample with regard to the average change in source type utilization offers the possibility of calculating a reliability benchmark for every single source type.

1. Which water sources do you use for domestic purposes in the rainy season? (Tick boxes)
2. If two or more sources are used, please rank (R:) them according to the amount of water withdrawn.

	CATEGORY	SOURCES	CODE	RAINY SEASON		DRY SEASON
WATER (DOMESTIC)	Modern sources	Private tap	[01]	☐ R:	3. Different in dry season? If yes, please fill in here →	☐ R:
		Public tap	[02]	☐ R:		☐ R:
		Bottled water	[03]	☐ R:		☐ R:
		Borehole	[04]	☐ R:		☐ R:
		Water vendor	[05]	☐ R:		☐ R:
		Canal	[06]	☐ R:		☐ R:
		Improved deep well	[07]	☐ R:		☐ R:
	Traditional sources	Unimproved deep well	[08]	☐ R:		☐ R:
		Shallow well	[09]	☐ R:		☐ R:
		Earth dam	[10]	☐ R:		☐ R:
		Oshana / Lake / Pan	[11]	☐ R:		☐ R:
		Rainwater	[12]	☐ R:		☐ R:
	Other: ...		[13]	☐ R:		☐ R:
	Comments: ...					

4. Where does your household normally receive food from in the rainy season? (Tick boxes)
5. If two or more food sources are used, please rank (R:) them according to the amount of food received.

	CATEGORY	SOURCES	CODE	RAINY SEASON		DRY SEASON
FOOD	Own production	Field / grain basket	[01]	☐ R:	6. Different in dry season? If yes, please fill in here →	☐ R:
		Garden / fruit trees	[02]	☐ R:		☐ R:
		Livestock (meat, milk, eggs)	[03]	☐ R:		☐ R:
		Self-collected wild food	[04]	☐ R:		☐ R:
		Self-caught fish	[05]	☐ R:		☐ R:
		Self-hunted bush meat	[06]	☐ R:		☐ R:
	Markets	Local market	[07]	☐ R:		☐ R:
		Supermarket	[08]	☐ R:		☐ R:
	Social network	Relatives	[09]	☐ R:		☐ R:
		Neighbors	[10]	☐ R:		☐ R:
	Donations	Church	[11]	☐ R:		☐ R:
		Government	[12]	☐ R:		☐ R:
	Other: ...		[13]	☐ R:		☐ R:
	Comments: ...					

Figure 2: Part A of the household drought risk survey. Upper plot assesses the water source types for domestic purposes, while the lower plot assesses the food source types.

Drought sensitivity

Sensitivity to drought is defined in this study as a household's dependence on unreliable water and food sources. Formally, the source-specific reliability levels are multiplied by the relative quantities of water and food obtained from the specific source types and subsequently divided by a households' total water and food demand. The resulting sensitivity scores were normalized on a scale from 0 (high, unfavourable) to 1 (low, favourable) using a min-max normalization technique.

Results

The results section will first present the seasonal consumption patterns and subsequently show the reliability levels of the individual water and food source types. Third, the drought sensitivity estimates are given, grouped according to certain socio-economic characteristics.

Seasonal consumption patterns

The households provided information on the number and type of food and water sources they utilize during an average rainy and dry season and indicated the relative quantities they withdraw. Figure 3 provides an overview of the shares of households that utilize specific water source types on a seasonal basis.

Modern water source types such as tap water and purchased water from vendors are used more intensively during the dry season, whereas the rainy season shows a higher utilization of traditional source types such as earth dams, shallow wells, and rainwater that make use of local water resources. This seasonal change between the water source types is statistically significant ($p < 0.05$). In particular, the urban agglomerations in Namibia (Oshakati and Outapi) show higher shares of tap water utilization in both seasons compared to rural Namibian areas. Furthermore, the data shows that the Angolan population does not use tap water, except in major urban agglomerations such as Ondjiva. This confirms the limited access people have to tap water, as the infrastructural endowment of the area is weaker than in Namibia. Instead, water vendors are a more common institution in Angola who often take over the role of public water supply but at higher costs.

With regard to the utilization of specific food source types, Figure 4 shows

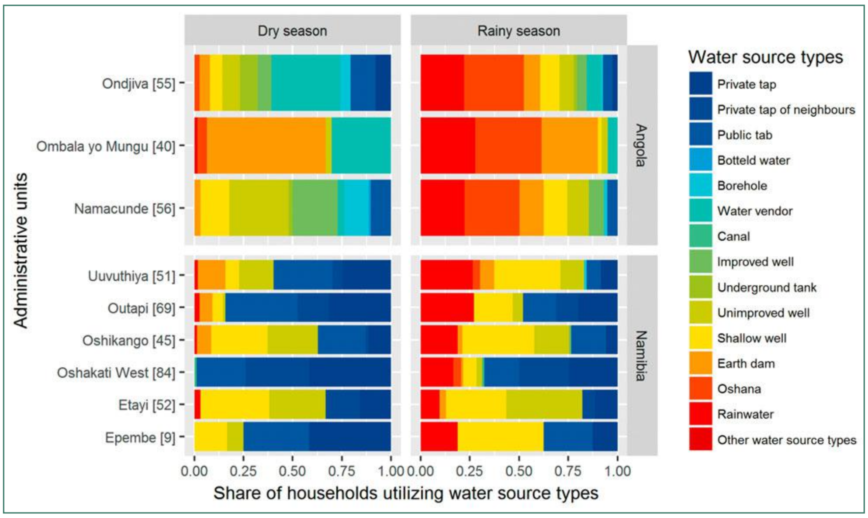

Figure 3: Relative utilization of water source types in the dry and the rainy season in administrative units. Values in brackets behind names of administrative units indicate the sample size.

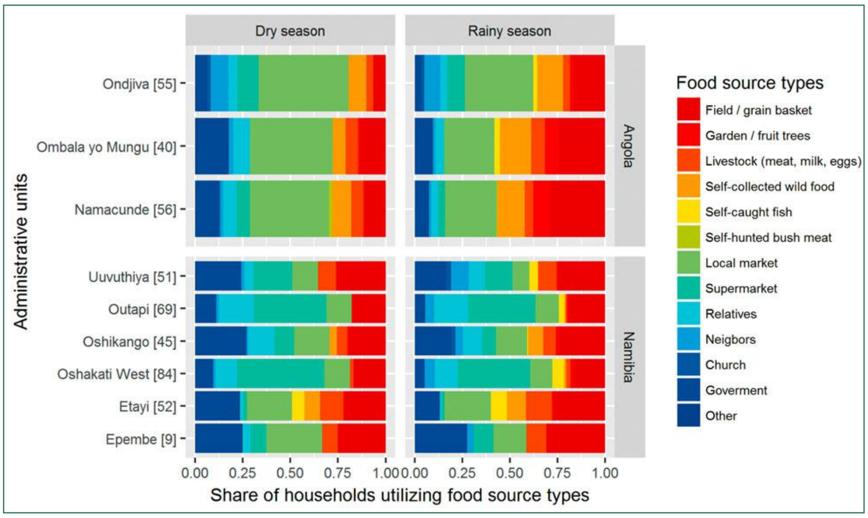

Figure 4: Relative utilization of food source types in the dry and the rainy season in administrative units. Values in brackets behind names of administrative units indicate the sample size.

that the change between rainy and dry season is less pronounced compared to the water consumption. Nevertheless, changes are evident particularly in Angola, with subsistence food products from own grain farming and livestock being important during the rainy season, while under dry conditions, local markets and governmental relief gain importance. The latter source type also plays an important role for Namibian households, for instance providing food to around 25% of the sampled households in Uuvuthiya, Oshikango, Etayi and Epembe constituencies. Thus, for many people, relief food items are essential to complement their diets even during the rainy season before the first harvests become available. Overall, nearly half of the households' food demand in rural areas is covered via neighbours, relatives, supermarkets and local markets. In urban areas, this share increases but subsistence food products still play a supplementary role and are acquired via the extended family network that reaches into the villages.

Source type reliability

Shifting the focus from the administrative units to the water and food source types and their reliability under dry conditions, Figure 5 illustrates the seasonal changes in utilization.

The coloured categories indicate whether a specific source type gained or lost importance from the rainy to the dry season. In other words, the coloured categories reveal whether a specific source type was (1) newly used in the dry season, (2) increasingly used, (3) persisted, (4) was decreasingly used, or even (5) was abandoned. If this last case appeared, the specific source type was not available anymore because of either quality or quantity constraints.

With respect to the water source types, the tap water sources show increased utilization while the traditional source types such as open water (iishana) and rainwater are abandoned in the dry season.

With regard to the food source types, the evaluation is less consistent. In general, subsistence food sources such as households' own agricultural activities decline in utilization during the dry season while types such as local markets and supermarkets as well as governmental relief gain importance. This visual impression is confirmed by quantifying the reliability of the source types. Table 1 presents the results on a normalized scale from 0 (less reliable) to 1 (more reliable).

Though the results of some source types such as "Canal" and "Self-hunted bush meat" have to be interpreted with caution since they are based on only a few cases, the overall ranking seems reasonable. As such, the most reliable water source types appear to be water vendors, tap water sources, and boreholes and deep wells that make use of groundwater that is less prone to drought conditions. Similarly, the most reliable food source types are governmental relief, market infrastructures, and relatives who provide food in the case of emergencies.

Drought sensitivity

From the findings above, drought sensitivity estimates can be calculated for every household by combining the specific source reliability benchmarks with the relative quantities obtained from each source type and the total household demand. Figure 6 illustrates the distribution of drought sensitivity scores in the sample, grouped according to rural and urban as well as Namibian and Angolan households.

It becomes obvious that rural households are more sensitive to drought events than urban citizens as their histograms are rather skewed to low values and the median sensitivity scores are closer to 0.

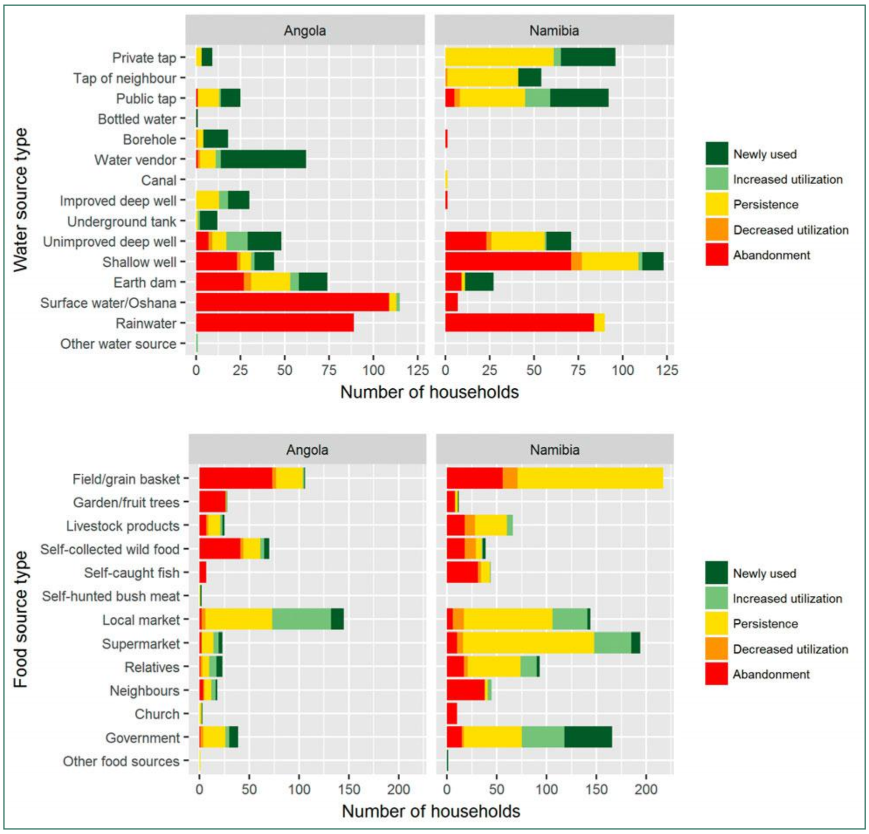

Figure 5: Seasonal changes in water and food source type utilization. The coloured categories indicate changes in utilization from the rainy to the dry season.

Though Namibian rural households show a similar distribution range of sensitivity values as their Angolan neighbours, they score better when considering their median, giving a hint to better infrastructural endowment of the Namibian area. By focusing on the urban households, the differences become more apparent. While the Namibian urban households show the best sensitivity scores (values close to 1), their Angolan counterparts give a more heterogeneous picture. This is particularly driven by urban agglomerations in Angola that are less well equipped as only the main town in the Cunene Province, Ondjiva, has good infrastructure.

Table 1: Reliability levels of water and food source types (0: less reliable; 1: more reliable).

Water source types	Reliability	Food source types	Reliability
Water vendor	1.00	Government	1.00
Public tap	0.98	Local market	0.92
Private tap	0.97	Supermarket	0.78
Tap of neighbour	0.84	Relatives	0.69
Borehole	0.84	Self-hunted bush meat	0.69
Improved deep well	0.84	Other food sources	0.69
Underground tank	0.83	Church	0.65
Unimproved deep well	0.81	Livestock products	0.56
Bottled water	0.79	Garden/fruit trees	0.51
Canal	0.78	Neighbours	0.51
Earth dam	0.77	Self-caught fish	0.48
Other water sources	0.76	Self-collected wild food	0.41
Shallow well	0.45	Field/grain basket	0.00
Surface water/*oshana*	0.26		
Rainwater	0.00		

Discussion

The following sections will specifically reflect on the results and the methodology applied against the background of the study's intention.

Reflection on results

The population utilizes a wide range of source types and responds to dry conditions by switching sources on a seasonal basis. While this aspect is assumed for developing countries, empirical surveys to explore this complexity are lacking (Elliott et al., 2017). This study confirms that the population follows complex water and food consumption patterns both structurally (multiple sources simultaneously) and temporally (different sources in the dry and the rainy seasons).

In addition, the estimates on water and food source type reliability that stem from the seasonal changes seem reasonable against the background of conventional classification systems (e.g., WHO & UNICEF, 2017). Traditional types that make use of local green and blue water are less reliable, since many households reduce the level of utilization or even abandon them during the dry season. Modern infrastructural types such as tap water and water vendors as well as local markets and supermarkets are often used when traditional types fail under dry conditions.

The sensitivity scores show that rural Angolan households are most sensitive to drought. This is a reasonable result, as the rural population has little access to modern water and food infrastructures compared to the rural Namibian households. Nevertheless, it is interesting to see that urban inhabitants are also closely connected to drought conditions, in particular with regard to consumed food items that are obtained from family members living in the villages. This link would have been hidden if the study had explored only the main food source (Crush & Caesar, 2017).

The drought sensitivity scores build on local knowledge of the population to depict their consumption patterns. Nevertheless, these scores can be only one part of a more holistic consideration of drought risk. Hence, the results will be integrated into a drought risk assessment

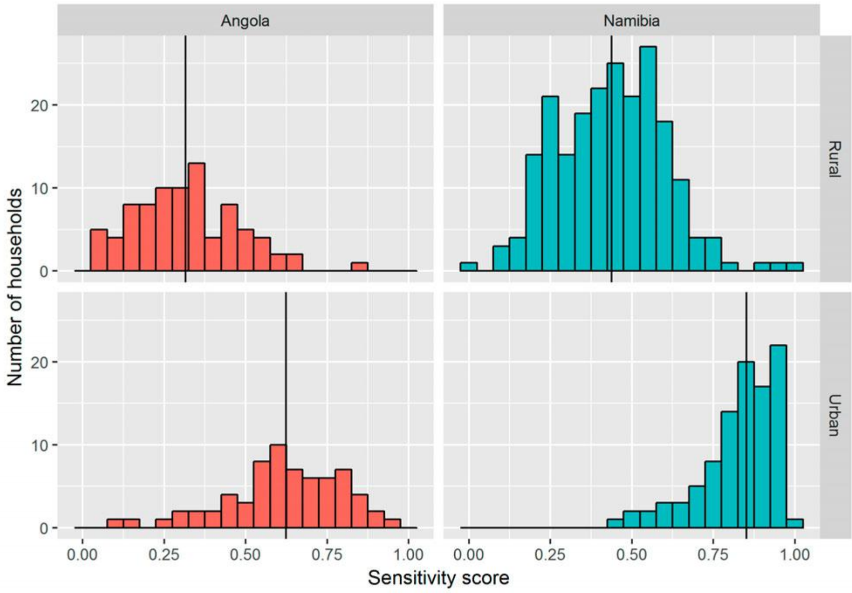

Figure 6: Histograms of drought sensitivity estimation of households, grouped according to settlement pattern and citizenship. The vertical line indicates the median sensitivity score for the respective groups.

tool that combines a physical hazard perspective (Luetkemeier et al., 2017) and empirical information on the coping capacities of the population into a single composite indicator, the Household Drought Risk Index (HDRI) (Luetkemeier, ISOE, unpubl.). In this index, drought risk is perceived as a combined outcome from both environmental stressors that act as hazards and societal characteristics of vulnerability that culminate in drought risk. This will enhance the decision base to improve short-term emergency responses and design targeted adaptation measures for drought policies and strategies (e.g., Republic of Namibia, 1997).

Methodological reflections

The complexity in consumption patterns is often overlooked, in particular in larger-scale assessments such as census surveys where only the main water and food sources are assessed (NSA, 2013; INE, 2016; Elliott et al., 2017). These surveys hide the underlying complexity and thus prevent more in-depth analyses. This study provides an adequate household sample size to analyse seasonal consumption patterns and gain insights into the way households act during the course of a year under rainy to dry conditions. In addition, the data offer the opportunity to estimate the reliability of water and food source types. These estimates stem solely from a socio-empirical survey and might help to support and complement the assessment of water resources from a hydrogeological perspective (Wanke et al., 2018).

Two major tasks for future research in this field require priority: First, the temporal resolution of the empirical assessment should be increased to quarterly or even monthly time steps with adequate questionnaire tools (i.e., by combining the ranking scheme with seasonal calendar assessments that are well known in food security assessments). Second, the drought sensitivity scores need to be validated (i.e., via household surveys during pronounced drought periods using conventional food security and nutrition surveys).

Conclusion

The assessment of drought sensitivity via the empirical investigation of seasonal water and food consumption patterns revealed that the population in the Cuvelai Basin utilizes a multi-resource mix to cope with drought situations. This mechanism is an expression of a self-regulated social-ecological system to alleviate the potential impact of drought. The risk of failure is mitigated by utilizing a broad range of source types that have varying levels of reliability under dry conditions. In this regard, modern water and food infrastructures serve as an important backup resource, if traditional, free sources fail.

Whereas the Namibian households show improved access to respective backup resources, their Angolan neighbours are less well equipped and hence require more investments in infrastructure development. Specifically, the extension of the tap water network in Angola is an important step to reduce the rural population's sensitivity to drought. Experiences gained in Namibia with the establishment of community water point committees can be a feasible solution (Schnegg & Bollig, 2016) as long as shortcomings in the institutional design can be resolved (Hossain & Helao, 2008). Furthermore, households require access to local market systems to sell and buy food items. Market systems need to be established in remote areas and people need to be enabled to purchase food if necessary (e.g., via grant or subsidy systems). Since many households rely on subsistence grain framing, the improvement of both the local production system (e.g., via small-scale irrigation schemes) and grain storage facilities (e.g., renewal of grain baskets) enhances people's ability to get through the dry season in general and drought events in particular. Positive experiences were already gained with the introduction of rain- and floodwater harvesting techniques (RFWH) alongside small-scale irrigation schemes and associated capacity development efforts to enhance technical and business skills, in particular among women (Kluge et al., 2008; Woltersdorf et al., 2014).

The methodology employed to assess seasonal consumption patterns proved to provide reasonable insights using an assessment procedure that is quick and simple to apply. Hence, if this ranking scheme procedure were to be incorporated into conventional household surveys such as regular census assessment (NSA, 2011), a continuous monitoring of consumption patterns and thus of drought sensitivity, among other phenomena, would be possible. Furthermore, the methodology is transferable to other regions with similar drought challenges, even if drought might affect additional consumption domains such as energy provision.

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References

Arouna, A. & Dabbert, S. (2009) Determinants of domestic water use by rural households without access to private improved water sources in benin: a seemingly unrelated Tobit approach. Water Resources Management, **24**, 1381–1398. doi:10.1007/s11269-009-9504-4

Baudoin, M.-A., Vogel, C., Nortje, K. & Naik, M. (2017) Living with drought in South Africa: lessons learnt from the recent El Niño drought period. International Journal of Disaster Risk Reduction, **23**, 128–137. doi:10.1016/j.ijdrr.2017.05.005.

Cardona, O.D., van Aalst, M.K., Birkmann, J., Fordham, M., McGregor, G., Perez, R., Pulwarty, R.S., Schipper, E.L.F. & Sinh, B.T. (2012) Determinants of Risk: Exposure and Vulnerability. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). (ed. by Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M. & Midgley, P.M., pp. 65–108. Cambridge University Press, Cambridge and New York.

Collier, P. & Dercon, S. (2014) African agriculture in 50 years: smallholders in a rapidly changing world? World Development, **63**, 92–101. doi:10.1016/j.worlddev.2013.10.001.

Crush, J. & Caesar, M. (2017) Food remittances: rural-urban linkages and food security in Africa, International Institute for Environment and Development (IIED), London.

Dagnew, D.C. (2012) Factors determining residential water demand in north western Ethiopia, the case of Merawi (project paper). Cornell University, Ithaca, New York.

Diao, X., Hazell, P. & Thurlow, J. (2010) The role of agriculture in African development. World Development, **38**, 1375–1383. doi:10.1016/j.worlddev.2009.06.011.

Ehret, C. (2001) Bantu expansions: re-envisioning a central problem of early African history. The International Journal of African Historical Studies, **34**, 5–41. doi:10.2307/3097285.

Elliott, M., MacDonald, M.C., Chan, T., Kearton, A., Shields, K.F., Bartram, J.K. & Hadwen, W.L. (2017) Multiple household water sources and their use in remote communities with evidence from Pacific Island countries. Water Resources Research, **53**, 9106–9117. doi:10.1002/2017WR021047

Falkenmark, M. & Rockström, J. (2006) The new blue and green water paradigm: breaking new ground for water resources planning and management. Journal of Water Resources Planning and Management, **132**, 129–132. doi:10.1061/(ASCE)0733-9496(2006)132:3(129)

Fiedler, J.L. (2013) Towards overcoming the food consumption information gap: strengthening household consumption and expenditures surveys for food and nutrition policymaking. Global Food Security, **2**, 56–63. doi:10.1016/j.gfs.2012.09.002

Freire-González, J., Decker, C. & Hall, J.W. (2017) The economic impacts of droughts: a framework for analysis. Ecological Economics, 132, 196–204. doi:10.1016/j.ecolecon.2016.11.005

Gleick, P.H. (1996) Basic water requirements for human activities: meeting basic needs. Water International, **21**, 83–92.

Hossain, F. & Helao, T. (2008) Local governance and water resource management: experiences from Northern Namibia. Public Administration and Development, **28**, 200–211. doi:10.1002/pad.499

INE (2016) Resultados definitivos do recenseamento geral da população e da habitação de Angola 2014 (census report). Instituto Nacional de Estatistica (INE), Luanda.

Inocencio, A.B., Padilla, J.E. & Javier, E.P. (1999) Determination of basic household water requirements. Discussion Paper no. 99-02 (revised). Philippine Institute for Development Studies, Makati City, Philippines.

Institute of Medicine (2005) Dietary reference intakes for energy, carbohydrate, fiber, fat, fatty acids, cholesterol, protein, and amino acids, National Academy Press, Washington, D.C.

Kluge, T., Liehr, S., Lux, A., Moser, P., Niemann, S., Umlauf, N. & Urban, W. (2008) IWRM concept for the Cuvelai Basin in northern Namibia. Physics and Chemistry of the Earth, Parts A/B/C, **33**, 48–55. doi:10.1016/j.pce.2007.04.005

Lavrakas, P. (2008) Probability proportional to size (PPS) sampling. Encyclopedia of Survey Research Methods, Sage Publications, Thousand Oaks CA, USA. doi:10.4135/9781412963947.n405

Luetkemeier, R. (2015) Household drought risk (HDRI) survey questionnaire [English/Portuguese]. (online resource, accessed on 06.03.2018). ISOE - Institute for Social-Ecological Research, SASSCAL - Southern African Science Service Centre for Climate Change and Adaptive Land Management. doi:10.13140/RG.2.2.25890.53446

Luetkemeier, R. & Liehr, S. (2015) Impact of drought on the inhabitants of the Cuvelai watershed: a qualitative exploration. Drought: research and science-policy interfacing (ed. by J. Alvarez, A. Solera, J. Paredes-Arquiola, D. Haro-Monteagudo, & H. van Lanen), pp. 41–48. CRC Press, Leiden, Netherlands. doi:10.1201/b18077-9

Luetkemeier, R., Stein, L., Drees, L. & Liehr, S. (2017) Blended drought index: integrated drought hazard assessment in the Cuvelai-Basin. Climate, **5**, 51. doi:10.3390/cli5030051

Mendelsohn, J. & Weber, B. (2011) Cuvelai. The Cuvelai Basin its water and people in Angola and Namibia (occasional paper), Development Workshop. Luanda, Angola.

Nauges, C. & Whittington, D. (2009) Estimation of water demand in developing countries : an overview. The World Bank research observer, **25**, 263–294.

NSA (2011) Census Namibia, census forms. Namibia Statistics Agency (NSA), Windhoek.

NSA (2013) Namibia 2011. Population & Housing Census Main Report, Namibia Statistics Agency (NSA), Windhoek.

Republic of Namibia (1997) National drought policy and strategy, National Drought Task Force, Republic of Namibia, Windhoek.

Schnegg, M. & Bollig, M. (2016) Institutions put to the test: community-based water management in Namibia during a drought. Journal of Arid Environments, **124**, 62–71. doi:10.1016/j.jaridenv.2015.07.009.

Seaman, J.A., Sawdon, G.E., Acidri, J. & Petty, C. (2014) The household economy approach. Managing the impact of climate change on poverty and food security in developing countries. Climate Risk Management, **4**, 59–68. doi:10.1016/j.crm.2014.10.001.

Smith, S.C. & Ubilava, D. (2017) The El Niño Southern Oscillation and economic growth in the developing world. Global Environmental Change, **45**, 151–164. doi:10.1016/j.gloenvcha.2017.05.007.

Thornton, P.K. & Herrero, M. (2015) Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. Nature Climate Change, **5**, 830–836. doi:10.1038/nclimate2754

UNISDR (2012) Disaster reduction in Africa. UNISDR informs (special issue on drought risk reduction). United Nations International Strategy for Disaster Reduction (UNISDR), Nairobi.

Wanke, H., Beyer, M., Hipondoka, M., Hamutoko, J., Gaj, M., Koenigerand, P. & Himmelsbach, T. (2018) The long road to sustainability: integrated water quality and quantity assessments in the Cuvelai-Etosha basin, Namibia. This volume.

WHO & UNICEF (2017) Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines., World Health Organization (WHO), United Nations Children's Fund (UNICEF), Geneva, Switzerland.

Wisner, B., Blaikie, P.M. & Cannon, T. (2003) At risk: natural hazards, people's vulnerability and disasters. Routledge Chapman & Hall, London, New York.

Woltersdorf, L., Jokisch, A. & Kluge, T. (2014) Benefits of rainwater harvesting for gardening and implications for future policy in Namibia. Water Policy, **16**, 124. doi:10.2166/wp.2013.061

References [CrossRef]

Arouna, A. & Dabbert, S. (2009) Determinants of domestic water use by rural households without access to private improved water sources in benin: a seemingly unrelated Tobit approach. Water Resources Management, **24**, 1381–1398. CrossRef

Baudoin, M.-A., Vogel, C., Nortje, K. & Naik, M. (2017) Living with drought in South Africa: lessons learnt from the recent El Niño drought period. International Journal of Disaster Risk Reduction, **23**, 128–137. CrossRef

Cardona, O.D., van Aalst, M.K., Birkmann, J., Fordham, M., McGregor, G., Perez, R., Pulwarty, R.S., Schipper, E.L.F. & Sinh, B.T. (2012) Determinants of Risk: Exposure and Vulnerability. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). (ed. by Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M. & Midgley, P.M., pp. 65–108. Cambridge University Press, Cambridge and New York.

Collier, P. & Dercon, S. (2014) African agriculture in 50 years: smallholders in a rapidly changing world? World Development, **63**, 92–101. CrossRef

Crush, J. & Caesar, M. (2017) Food remittances: rural-urban linkages and food security in Africa, International Institute for Environment and Development (IIED), London.

Dagnew, D.C. (2012) Factors determining residential water demand in north western Ethiopia, the case of Merawi (project paper). Cornell University, Ithaca, New York.

Diao, X., Hazell, P. & Thurlow, J. (2010) The role of agriculture in African development. World Development, **38**, 1375–1383. CrossRef

Ehret, C. (2001) Bantu expansions: re-envisioning a central problem of early African history. The International Journal of African Historical Studies, **34**, 5–41. CrossRef

Elliott, M., MacDonald, M.C., Chan, T., Kearton, A., Shields, K.F., Bartram, J.K. & Hadwen, W.L. (2017) Multiple household water sources and their use in remote communities with evidence from Pacific Island countries. Water Resources Research, **53**, 9106–9117. CrossRef

Falkenmark, M. & Rockström, J. (2006) The new blue and green water paradigm: breaking new ground for water resources planning and management. Journal of Water Resources Planning and Management, **132**, 129–132. CrossRef

Fiedler, J.L. (2013) Towards overcoming the food consumption information gap: strengthening household consumption and expenditures surveys for food and nutrition policymaking. Global Food Security, **2**, 56–63. CrossRef

Freire-González, J., Decker, C. & Hall, J.W. (2017) The economic impacts of droughts: a framework for analysis. Ecological Economics, 132, 196–204. CrossRef

Gleick, P.H. (1996) Basic water requirements for human activities: meeting basic needs. Water International, **21**, 83–92. CrossRef

Hossain, F. & Helao, T. (2008) Local governance and water resource management: experiences from Northern Namibia. Public Administration and Development, **28**, 200–211. CrossRef

INE (2016) Resultados definitivos do recenseamento geral da população e da habitação de Angola 2014 (census report). Instituto Nacional de Estatistica (INE), Luanda.

Inocencio, A.B., Padilla, J.E. & Javier, E.P. (1999) Determination of basic household water requirements. Discussion Paper no. 99-02 (revised). Philippine Institute for Development Studies, Makati City, Philippines.

Institute of Medicine (2005) Dietary reference intakes for energy, carbohydrate, fiber, fat, fatty acids, cholesterol, protein, and amino acids, National Academy Press, Washington, D.C.

Kluge, T., Liehr, S., Lux, A., Moser, P., Niemann, S., Umlauf, N. & Urban, W. (2008) IWRM concept for the Cuvelai Basin in northern Namibia. Physics and Chemistry of the Earth, Parts A/B/C, **33**, 48–55. CrossRef

Lavrakas, P. (2008) Probability proportional to size (PPS) sampling. Encyclopedia of Survey Research Methods, Sage Publications, Thousand Oaks CA, USA. CrossRef

Luetkemeier, R. (2015) Household drought risk (HDRI) survey questionnaire [English/Portuguese]. (online resource, accessed on 06.03.2018). ISOE - Institute for Social-Ecological Research, SASSCAL - Southern African Science Service Centre for Climate Change and Adaptive Land Management. CrossRef

Luetkemeier, R. & Liehr, S. (2015) Impact of drought on the inhabitants of the Cuvelai watershed: a qualitative exploration. Drought: research and science-policy interfacing (ed. by J. Alvarez, A. Solera, J. Paredes-Arquiola, D. Haro-Monteagudo, & H. van Lanen), pp. 41–48. CRC Press, Leiden, Netherlands. CrossRef

Luetkemeier, R., Stein, L., Drees, L. & Liehr, S. (2017) Blended drought index: integrated drought hazard assessment in the Cuvelai-Basin. Climate, **5**, 51. CrossRef

Mendelsohn, J. & Weber, B. (2011) Cuvelai. The Cuvelai Basin its water and people in Angola and Namibia (occasional paper), Development Workshop. Luanda, Angola.

Nauges, C. & Whittington, D. (2009) Estimation of water demand in developing countries : an overview. The World Bank research observer, **25**, 263–294. CrossRef

NSA (2011) Census Namibia, census forms. Namibia Statistics Agency (NSA), Windhoek.

NSA (2013) Namibia 2011. Population & Housing Census Main Report, Namibia Statistics Agency (NSA), Windhoek.

Republic of Namibia (1997) National drought policy and strategy, National Drought Task Force, Republic of Namibia, Windhoek.

Schnegg, M. & Bollig, M. (2016) Institutions put to the test: community-based water management in Namibia during a drought. Journal of Arid Environments, **124**, 62–71. CrossRef

Seaman, J.A., Sawdon, G.E., Acidri, J. & Petty, C. (2014) The household economy approach. Managing the impact of climate change on poverty and food security in developing countries. Climate Risk Management, **4**, 59–68. CrossRef

Smith, S.C. & Ubilava, D. (2017) The El Niño Southern Oscillation and economic growth in the developing world. Global Environmental Change, **45**, 151–164. CrossRef

Thornton, P.K. & Herrero, M. (2015) Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. Nature Climate Change, **5**, 830–836. CrossRef

UNISDR (2012) Disaster reduction in Africa. UNISDR informs (special issue on drought risk reduction). United Nations International Strategy for Disaster Reduction (UNISDR), Nairobi.

Wanke, H., Beyer, M., Hipondoka, M., Hamutoko, J., Gaj, M., Koenigerand, P. & Himmelsbach, T. (2018) The long road to sustainability: integrated water quality and quantity assessments in the Cuvelai-Etosha basin, Namibia. This volume. CrossRef

WHO & UNICEF (2017) Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines., World Health Organization (WHO), United Nations Children's Fund (UNICEF), Geneva, Switzerland.

Wisner, B., Blaikie, P.M. & Cannon, T. (2003) At risk: natural hazards, people's vulnerability and disasters. Routledge Chapman & Hall, London, New York.

Woltersdorf, L., Jokisch, A. & Kluge, T. (2014) Benefits of rainwater harvesting for gardening and implications for future policy in Namibia. Water Policy, **16**, 124. CrossRef

Rangelands

Rangeland monitoring and assessment: a review

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Abstract: Rangelands provide vast landscapes for grazing and foraging for livestock and wildlife. Services of rangelands are diverse and generally provide food for millions of the world's population, especially the rural and sometimes poor communities. Despite the importance of rangelands, they are also threatened by global change including land use and climate change. Land-use change is exacerbated by the ever-increasing human population, which is projected to reach over 9 billion in 2050. Meanwhile, climate change in the form of erratic rainfall and increasing temperatures, favours increasing woody cover leading to bush encroachment and recurrent droughts. The objective of this overview article is to provide a synopsis of the key areas covered by the subsequent articles, and drawing upon a wider body of literature. Key issues highlighted in this chapter are the definition of rangeland landscapes, their role and threats such as bush encroachment, land degradation (e.g. soil erosion), indicators for monitoring (i.e. quality of grass, trees, and legumes), and assessment of rangelands using in situ and remote sensing techniques. The threats of soil erosion, fire, and bush encroachment are discussed in relation to the functioning of these landscapes for wildlife and livestock. However, in situ and remote sensing techniques provide the opportunity to assess the status or condition, quality, and extent of rangeland environments.

Resumo: As pastagens oferecem vastas paisagens para o pastoreio e procura de alimento ao gado e a animais selvagens. Os serviços das pastagens são diversos e geralmente fornecem alimento a milhões de pessoas no mundo, em especial nas comunidades rurais e, por vezes, pobres. Apesar da importância das pastagens, estas estão também ameaçadas pelas alterações globais, incluindo o uso das terras e as alterações climáticas. A alteração do uso das terras é exacerbada pelo constante crescimento da população humana, a qual deverá atingir os 9 mil milhões em 2050. Entretanto, as alterações climáticas geram precipitação irregular e o aumento da temperatura, os quais favorecem o aumento da cobertura lenhosa, levando ao *bush encroachment* e a secas recorrentes. O objectivo deste artigo de revisão é fornecer uma sinopse das áreas chave que serão abordadas em artigos subsequentes. Para atingir este objectivo, foi realizada uma revisão bibliográfica, incluindo diversos capítulos deste livro. As questões-chave destacadas neste capítulo são a definição da paisagem de pastagem, o seu papel e suas ameaças, tais como a densificação de plantas lenhosas e degradação da terra (e.x.: erosão do solo), indicadores para monitorização, i.e., qualidade das gramíneas, árvores e legumes, e avaliação das pastagens recorrendo ao uso de técnicas *in situ* e de detecção remota. As ameaças em destaque identificadas incluem a erosão do solo, o fogo e a densificação de plantas lenhosas, as quais são alguns dos problemas que afectam paisagens críticas para os animais selvagens e o gado. No entanto, técnicas *in situ* e de detecção remota oferecem a oportunidade de avaliar o estado ou a condição, a qualidade e a extensão dos ambientes de pastagem.

Introduction

Rangelands are defined as landscapes that provide grazing and foraging for livestock and wildlife, where the natural vegetation consists of native grasses, grass-like plants, flowering plants, and shrubs, as well as introduced plant species that are naturalised (Craggs, 2017). Rangelands cover about 51% of the world's land surface (Child & Frasler, 1992) and provide food for millions of the world's population. Rangeland services include the provision of grazing resources for commercial and subsistence livestock or game farming (Naidoo et al., 2013), harvesting of wild products, carbon sequestration, pollination services, and freshwater sources. Millions of people rely on rangelands for their daily sustenance and many are from rural and sometimes poor communities.

In the Eocene epoch (34 to 56 million years ago), the colonisation of new habitats coupled with the exploitation of new, diverse food resources led to the rapid diversification of large herbivores, especially ruminants (Prothero & Foss, 2007). Vestiges of this high diversity of indigenous herbivores are still visible in Africa, especially in the open grassy biomes (Turpie & Crowe, 1994), and are related to the high availability and diversity of food plants. In terms of their abundance, there are an estimated 75 million wild ruminants and 3.5 billion domesticated ruminants in the world (Hackmann & Spain, 2010). In 2014, annual human meat consumption amounted to 82 million tons of ruminant meat (excluding bush meat and meat from game and camelids). This corresponds to 1,684 million individual cattle and buffalo and 2,165 million individual sheep and goats (www.fao.org). One problem with having so many animals on the land is that they have a negative impact on the environment and contribute significantly to the production of greenhouse gases (Steinfeld et al., 2006).

Rapid growth in the human population has significant implications for rangeland utilisation and management. The population in 2050 is projected to be more than 9 billion and most of the increase is estimated to be in developing countries, with more than half in Africa (UNPD, 2015). The population of sub-Saharan Africa is growing at an annual rate of 2.6%. The rapid increase in the human population is placing new demands on rangelands to provide food and shelter to meet its needs, as a result often leading to unprecedented changes in land cover and land use (Thornton, 2010; FAO, 2010). Overexploitation of rangelands leads to land degradation and threatens the quality and productivity of these ecosystems (FAO 2010). Hahn et al. (2005) defined land degradation as the reduction or loss of biological or economic productivity as a consequence of inappropriate land-use practices.

Other global change pressures, including rising temperatures and the increased occurrence of extreme events such as drought and erratic rainfall patterns, are also impacting on the functioning of rangeland systems (Palmer & Bennett, 2013). Drought, bush encroachment, and invasion by alien species are increasing threats on the African continent and hence on rangeland productivity. Increasing anthropogenic CO_2 in the atmosphere is having a fertilisation effect on C3 trees, thereby fuelling the phenomenon of bush or woody encroachment. Furthermore, increasing warming (projected to be 3–5 °C by the end of the century) will favour C4 grasses in place of C3 grasses (Scholes & Archer, 1997; Bond et al., 2003; Palmer, 2003). Global change impacts could be even severer for arid and semi-arid rangelands in southern Africa.

Threats faced by rangeland environments

Large areas of Africa are covered by savanna and grassland systems whose productivity is dependent mainly on the seasonality of climatic variables (rainfall and temperature). African savannas are both utilised as habitats for wildlife (e.g. the "big five") and for livestock and food crop production, thus supporting the livelihoods of millions of people living in these systems. However, rapid changes in land use and anthropogenic climatic changes are negatively impacting on wildlife numbers and the sustainability of rangelands (Lehmann et al., 2009). Harris et al. (2014) investigated the resilience of vegetation cover in relation to disturbance and found different results for different biomes in southern Africa. For some areas (e.g. the western and northern savanna region of Namibia and the eastern part of South Africa), the results imply strong potential impacts of anthropogenic or climatic change on vegetation, which will certainly lead to changes in food availability and also biodiversity. In general, threats to rangeland, including bush encroachment, habitat fragmentation, overgrazing, soil erosion, and human-induced fires, are the major causes of land degradation in many African rangelands (Murphy et al., 2016 and references therein).

Key indicators for the extent of land degradation are the types of soil erosion that might be found in an area. For example, there is evidence that gully systems are cutting into urban environments in Angola (see SASSCAL task 171) or in agricultural fields in the Swartland region of South Africa (Olivier et al., 2018), while in Namibia, critical landscapes for livestock and wildlife have been lost as a result of erosion (Pringle et al., 2011). Key research related to this has focused on the efficacy of restoration from both ecological and socio-economic perspectives (Zimmerman et al., 2018).

There has also been a lengthy debate about the differences in water consumption of trees and grasses in savanna ecosystems. Discussions have centred on the degree of competition for water between trees and grasses under different environmental settings, as well as the consequences of bush encroachment on the water balance and especially groundwater recharge (e.g. Scholes & Archer, 1997; Scanlon et al., 2006; O'Connor et al., 2014). For southern African rangelands, with their widespread problem of bush encroachment, robust information is missing about the interaction of bushes and trees with the lower layer of grasses, herbs, and dwarf shrubs, and how this might affect the dynamics of water in plants and in the soil (Christian, 2010). Thus, SASSCAL studied these interactions with different methodological approaches. Using field monitoring techniques, measurements were taken of the soil water dynamics of bush-encroached areas as well as de-bushed areas since 2007 on a commercial farm in the central Namibian thorn-bush savanna and, since 2014, on two other farms (Groengroeft et al., 2018).

Rangelands are thought to have been highly productive before modern humans disrupted their efficient water and nutrient cycles. The appropriate management of herbivores, to provide sufficient rest for grazed grasses to regain their vigour, can go a long way towards recovering water and nutrient cycles over extensive areas of rangeland. Intensive management can also be applied on a few small areas, such as rain water harvesting measures to enhance infiltration into the ground and thereby support the growth of natural grasses and planted trees. This was attempted at three sites by digging contour ditches, and by constructing ponding banks at one of those sites. Earth-moving machinery was used at the 30 ha rural site, while contour ditches were manually dug with pick and spade at the two smaller urban sites. Diverse tree species were planted below contour ditches for different functions and products, including chop-and-drop mulching, tall protective canopies, and edible leaves, fruits and pods (Zimmerman et al., 2018).

Drought as a consequence of climate change causes devastating problems for rangelands and livestock production systems in Africa. The occurrence of drought limits the carrying capacity of rangelands and the number of animals that can be kept on them. Livestock mortality is often relatively high during drought periods. This has important implications for the livelihoods of local communities because of the loss of employment, production, and income (Tambo et al. 2017). Careful management is necessary to balance human demands and landscape capacities to avoid overexploitation. An assessment of rangeland condition, through the identification of key indicators associated with vegetation, soil, and water, is necessary in order to inform decision-makers on the planning and management of rangelands.

What are the key indicators for assessing rangelands?

Vegetation composition is the overarching key factor that determines rangeland quality. The presence of palatable food plants and the abundance of unpalatable plant species determine the carrying capacity of a landscape for all herbivores. The composition of the vegetation is mainly driven by the existing soil characteristics (geology), water availability, geographical features, and prevailing climatic conditions. Vegetation composition, and consequently food plant availability, is affected by changes in temperature and/or rainfall. In order to describe the overall quality of a given landscape, different indicators are used. For example, biomass is used as an indicator of productivity, while digestibility or biochemical concentrations (e.g. protein, nitrogen, lignin, fibre) are used as indices of plant quality. However, other factors, such as the presence of chemical and mechanical defences in plants (e.g. toxic food compounds or thorns and hairs), are often not included in these assessments and might lead to misunderstanding of the productivity and quality of a given landscape. The parameters describing the overall quality of a given rangeland are also not in a steady state and will always change with land use and climate. A description of these dynamic interactions is provided in the following sections.

Influence of large herbivores on vegetation

Since the evolution of large herbivores, terrestrial ecosystems have been highly influenced in shape and function by browsing and grazing animals, which modify primary production, nutrient cycles, soil properties, and fire regimes, with subsequent impacts on other biota (McNaughton et al., 1988; Pastor & Naiman, 1992; Olff & Ritchie, 1998; Wardle et al., 2004; Archibald et al., 2005). The distribution of large herbivores determines the vegetation composition of terrestrial ecosystems due to, for example, feeding damage (Rooney, 2001; Bobrowski et al., 2015) and trampling (Van der Wal et al., 2001; Cumming & Cumming, 2003), but also seed dispersal (Gill & Beardall, 2001; Hülber et al., 2005; Benthien et al., 2016). Additionally, plant chemical composition, morphology, and fertility change in response to feeding damage (Stolter et al., 2005; Stolter, 2008). The key factor behind this ecosystem modification is simply the food selection patterns of animals.

Biodiversity, chemical diversity, resource availability, and feeding decisions of large herbivores

In terms of plant biodiversity in Africa, most people will immediately think of the closed canopy tropical forests. Although the tropical grassy biomes, including savannas, are lower in plant diversity than the tropical forests (Kier et al., 2005; Barthlott et al., 2007; Harris et al., 2014), they also comprise a high number of species (Murphy et al., 2016). Depending on annual rainfall, species richness of vascular plants reported from the observatories of SASSCAL (http://www.sasscalobservationnet.org/; Jürgens et al., 2018) may be as high as 45.1 species per ha for the woodland savanna, 57.9 for thorn-bush savanna, 26.4 for dwarf shrub savanna, and 61.1 for the succulent karoo (in areas with high annual rainfall). Due to their long co-existence with wild, free-ranging herbivores and the natural, frequent occurrence of fire, these ecosystems are to some extent adapted to both forms of disturbance (Ratnam et al., 2011). They are also characterised by a large number of different life forms (e.g. woodland and thorn-bush savanna have as many as 11 different life forms; Jürgens et al., 2010). While woodland savanna is characterised mainly by a grassland-tree community, there is a shift to a grassland community interspersed with a relatively high proportion of different dwarf shrubs and small bushes in the thorn-bush savanna. In the thorn-bush savanna the diversity of grasses is also extraordinarily high. However, small shrubs and herbs, such as *Monechma genistifolium* and different wild legumes, often serve as food for wild herbivores. They can also be an additional, supplementary, alternative food resource for livestock, for example in the dry season when food availability is restricted (Madibela et al., 2018). Their utilisation by herbivores, as well as their general nutritional quality, is poorly known. More than 150 trees, bushes, and shrubs and more than 30 herbs and forbs in Namibia alone are reported to serve as food plants (Le Roux et al., 2009, and Stolter, unpublished data). Within SASSCAL, we aim to produce a database of nutritional values including these important but often neglected food plant species (Stolter 2018a).

However, when viewed from the perspective of a herbivore, we would like to extend the concept of "plant diversity" to also include "plant chemical diversity". Plants consist of a high number of different plant compounds such as proteins, amino acids, lipids, fibre fractions, and plant secondary metabolites. The chemical composition of a plant is species-specific, but also changes in response to external factors. For example, plants react to damage caused by herbivory, but also to enhanced UV radiation, drought stress, etc. When subjected to such stressors, changes occur in the concentration of nutritional compounds (e.g. protein) but also in specific defence compounds such as plant secondary metabolites (PSM) (Tegelberg et al., 2003; McKiernan et al., 2014). Thousands of different PSMs have evolved in plants and the composition varies between plant species (e.g. Stolter et al., 2005). Even within each single chemical class of PSM (e.g. tannins, terpenoids) there can be thousands of compounds (Iason et al., 2012) differing in their mode of action as a deterrent. Furthermore, the relative concentrations of specific compounds differ between individual plants of the same species growing on different sites (Stolter et al., 2010). There are also differences between different plant parts (e.g. twigs and leaves; Stolter, 2008) and differences between seasons (Stolter et al., 2013). This high variability (only demonstrated here for PSMs) co-varies with other compounds, for example different fibre fractions. Hence, the large number and variety of different plant compounds contributes to a multidimensional feeding environment for herbivores (Villalba et al., 2002), where the animals have to choose for each bite which plant or plant part to ingest. The impact of different factors on food quality and food availability for large herbivores will be further discussed in the subsequent chapter (Stolter et al., 2018a).

Bush encroachment

Bush encroachment is often seen as a sign of unsustainable land use caused by different factors. One driver of the transformation of the savanna ecosystem is habitat utilisation. In this respect, overgrazing, as well as the shift from wild herbivores to cattle, might be an important factor. Within SASSCAL, we investigated the effect of herbivore damage on plant and the associated consequences on food selection of livestock. Furthermore, we conducted standardised experiments and field surveys investigating the habitat utilisation of, and feeding damage caused by, different large herbivores. Knowledge on habitat utilisation, food selection of different herbivores, and the consequent plant response might help to understand how herbivores influence the vegetation, and therefore aid in the development of appropriate management strategies to prevent or defend bush encroachment (Stolter et al., 2018b).

Fire

In addition to the factors mentioned above, fire can have severe impacts on the vegetation, for example by slowing down the successional processes through which grassland is converted to forest vegetation (Backéus, 1992; Bond & Keeley, 2005). Therefore, fire can also have a regulatory function as it is crucial in interrupting the transition processes from one vegetation state to another (Joubert et al., 2012). By influencing the light, vegetation, and soil characteristics of rangelands, fires can lead to severe changes, not only in vegetation composition but also in the chemical make-up of plants. In consequence, this also affects the feeding decisions of the associated herbivore community as well as biodiversity. Therefore, all human-induced changes to the natural fire regime, including the use of fire for management purposes, influences the natural dynamics of savanna vegetation and causes changes in the composition, biodiversity, and function of terrestrial ecosystems (Bond & van Wilgen, 1996; Bird & Cali, 1998; Guyette et al., 2002).

Fire is often used extensively as a management tool for rangelands. One reason for using fire is to maintain productive grassland by removing moribund, poor-quality grasses. It is also used because of the "fertilising" effects of fire (Hobbs & Schimel, 1984; Ojima et al., 1994; Úbeda et al., 2005), which can lead to increased plant growth immediately after its occurrence (Van de Vijver et al., 1999; Giardina & Rhoades, 2001; Rieske et al., 2002). Furthermore, plants have to compensate for the lost, burnt tissue. Similar to the response that plants have to herbivory (Stolter, 2008), and depending on the plant species affected, this might lead to improved plant quality after a fire has passed through, for example the presence of a greater concentration of protein. However, depending on the frequency and severity of fire, essential nutrients such as nitrogen will be lost during the burning process either due to volatilisation or to their conversion into inorganic compounds. The latter will be lost by leaching processes during the first rainfall after the fire has occurred (Knicker, 2007). Therefore, we investigated the effect of naturally occurring fires on different parameters (e.g. vegetation composition and changes in forage quality, soil characteristics, biodiversity, abundances of mammals and insects, and large herbivore distribution; Joubert et al., 2018).

Nevertheless, naturally occurring fires are often suppressed by policy or their appearance is limited due to a serious reduction of fuel loads caused by overgrazing. Consequently, this reduction of fire is a major factor for the transition of grassland into bushy areas (Joubert et al., 2008).

Rangeland assessment and monitoring

There are two main techniques for assessing rangeland extent, condition, and quality: conventional field data collection and remote sensing. Conventional techniques are often tedious and laborious. On the other hand, remote sensing techniques provide a bird's-eye view of landscapes with measurements that can be repeated on a regular basis. For remote sensing techniques, field data is often required to calibrate and validate prediction models, although this does not necessarily need to be extensive. The chapter on rangelands in this volume shall present various in situ and remote sensing data collection techniques for the assessment of rangeland condition and health.

In situ based assessments

Conventionally, the assessment of rangeland has been done using field-based or in situ measurements. The field-based methods are used to collect information about the state or condition of soils, vegetation, and water. In the rangeland chapter, the use of a series of in situ methods is described in several articles, focusing on forage quality, landscape function, rangeland rehydration, fire, and bush encroachment.

While remote sensing can give large-scale overviews across landscapes, field studies are needed for concrete management, calibration, and validation ("ground truthing") of the resulting products. For example, habitat utilisation by large herbivores does not exclusively depend on biomass, protein, or fibre concentration. Factors like social behaviour (e.g. home ranges and territories) and geographical features (e.g. proximity to water holes), but also climatic conditions (e.g. temperature), influence the habitat utilisation of animals. Furthermore, predation risk and hunting pressure have an enormous impact on the distribution of animals. We discuss this in more detail in the article on bush encroachment management. Furthermore, details about plant quality can only be measured in the field, because we are not able to translate every plant characteristic into a spectral signal measurable from satellites. For grazers, the sole use of remote sensing to provide an estimate of habitat quality might be less problematic, as these animals feed mainly on grass, which is not highly defended, either mechanically or chemically. However, mechanical defences (e.g. the length of thorns) can only be seen in the field and the presence of some poisonous plant compounds, which might correlate with high nutritional quality (e.g. such as is frequently found in plants of the Fabaceae family), can unfortunately not yet be captured by remote sensing. Therefore, in-situ (field-based) studies are of

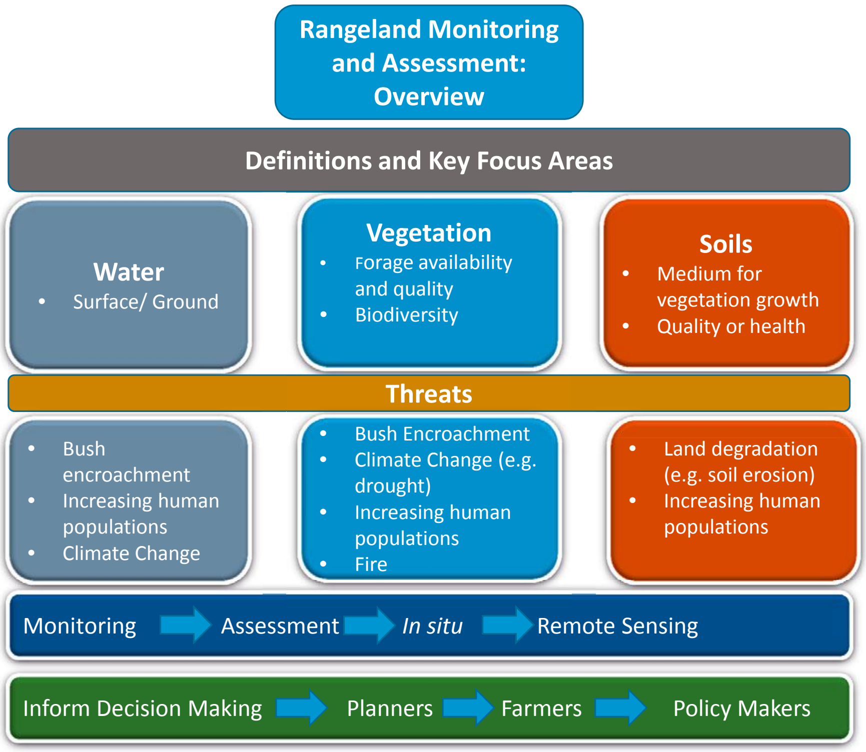

Figure 1: Schematic representation of the rangeland chapter.

high importance to confirm plant chemical composition, food utilisation, and habitat utilisation in order to understand habitat quality for different herbivores in the landscape. Due to the reasons mentioned above, we used different techniques to determine habitat utilisation of different animals in the field. Those methods can range from the use of photo traps and animal counts (observation) to GPS-collared animals and faecal dung counts (see article on fire and bush encroachment). Different methods are also available to study food utilisation, such as the estimation of damage caused by herbivory, analyses of rumen and faeces content, as well as personal observations. A brief description on the analyses concerned with nutritional quality can be found in the corresponding infobox by Stolter (2018b).

Remote sensing techniques

Satellite remote sensing provides an alternative approach for mapping vegetation cover, state, and condition for wider geographic areas and over relatively long time periods (Harris et al., 2014). The estimation of vegetation indicators in rangelands has been successfully applied using hyperspectral data, both field spectrometer and airborne data (Mutanga & Skidmore, 2004; Skidmore et al., 2010; Knox et al., 2012; Ramoelo et al., 2013), as well as satellite multispectral data (Harris et al., 2014; Schucknecht et al., 2017). Empirical statistical methods are used to achieve this, often using vegetation indices. The approach involves the determination of the relationship between in situ measured vegetation condition indicators, such as quality and availability (biomass, dry matter mass per unit area), and the vegetation indices such as the normalised difference vegetation index (NDVI; Rouse et al., 1974) and a second generation of vegetation indices such as the red edge position (REP) (Curran et al., 1991; Cho & Skidmore, 2006) and narrow band indices (Mutanga & Skidmore, 2004; Mutanga & Skidmore, 2007; Ramoelo et al., 2012; Ramoelo et al., 2015a; Ramoelo et al., 2015b). The next generation of satellite constellations incorporate the red edge band strategically, which enables forage quality estimation using nitrogen concentrations (N) as an indicator. For example, the Sentinel-2 satellite developed and launched by the European Space Agency (ESA) provides freely-available images that – like Landsat and MODIS – could be useful to improve the assessment of vegetation and crop productivity. In this study, the Sentinel-2 data (red edge based indices) were used to estimate leaf N concentrations, while a MODIS-based leaf area index model was used to estimate regional and time-series products for herbaceous vegetation (Task 229) (Stolter et al. 2018a).

Conclusions

It is evident that rangelands are under pressure due to ever-changing climate events and increasing human populations. As a result, threats such as bush encroachment and land degradation (e.g. soil erosion) are evident. Nevertheless, there was significant progress in SASSCAL in assessing the status or condition, extent, and quality of rangelands using both in situ and spatially-explicit remote sensing approaches. Key issues addressed in this chapter focused on rangeland quality – grass, trees and legumes, fire impact, bush encroachment, and creative use of rangelands – and finally, on rangeland management and dehydration processes (Fig. 1). Future research should focus on a collaborative development of a regional, integrated, and seamless rangeland monitoring framework for southern Africa.

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References

Archibald, S., Bond, W., Stock, W. & Fairbanks, D. (2005) Shaping the landscape: fire–grazer interactions in an African savanna. *Ecological Applications*, **15**, 96-109.

Backéus, I. (1992) Distribution and vegetation dynamics of humid savannas in Africa and Asia. *Journal of Vegetation Science*, **3**, 345-356.

Barthlott, W., Hostert, A., Kier, G., Koper, W., Kreft, H., Mutke, J., Rafiqpoor, M.D. & Sommer, J.H. (2007) Geographic patterns of vascular plant diversity at continental to global scales. *Erdkunde*, **61**, 305-315.

Benthien, O., Bober, J., Castens, J. & Stolter, C. (2016) Seed dispersal capacity of sheep and goats in a near-coastal dry grassland habitat. *Basic and Applied Ecology*, **17**, 508-515.

Bird, M. & Cali, J. (1998) A million-year record of fire in sub-Saharan Africa. *Nature*, **394**, 767-769.

Bobrowski, M., Gillich, B. & Stolter, C. (2015) Modelling browsing of deer on beech and birch in northern Germany. *Forest Ecology and Management*, **358**, 212-221.

Bond, W., Midgley, G. & Woodward, F. (2003) The importance of low atmospheric CO2 and fire in promoting the spread of grasslands and savannas. *Global Change Biology*, **9**, 973-982.

Bond, W.J. & van Wilgen, B.W. (1996) Why and how do ecosystems burn? *Fire and Plants*, pp. 16-33. Springer.

Bond, W.J. & Keeley, J.E. (2005) Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems. *Trends in Ecology & Evolution*, **20**, 387-394.

Child, R.D. & Frasler, G. (1992) ARS range research. *Rangelands Archives*, **14**, 17-32.

Cho, M.A. & Skidmore, A.K. (2006) A new technique for extracting the red edge position from hyperspectral data: The linear extrapolation method. *Remote Sensing of Environment*, **101**, 181-193.

Christian, C. (2010) Desk top Study on the Effect of Bush Encroachment on Groundwater Resources in Namibia. Pages 109 and Appendix. Colin Christian & Associates CC, Windhoek.

Craggs, G. 2017. Rangelands: Critical to the environment and under constant threat. Future Directions International. Dalkeith, Australia. http://www.futuredirections.org.au/publication/rangelands-critical-environment-constant-threat/ (Accessed on the 30 July 2017).

Cumming, D.H. & Cumming, G.S. (2003) Ungulate community structure and ecological processes: body size, hoof area and trampling in African savannas. *Oecologia*, **134**, 560-568.

Curran, P.J., Dungan, J.L., Macler, B.A. & Plummer, S.E. (1991) The effect of a red leaf pigment on the relationship between red edge and chlorophyll concentration. *Remote Sensing of Environment*, **35**, 69-76.

FAO (Food and Agriculture Organization of the United Nations). 2010. Land degradation assessment in drylands (LADA): http://www.fao.org/nr/lada/ (accessed April 2017).

Giardina, C.P. & Rhoades, C.C. (2001) Clear cutting and burning affect nitrogen supply, phosphorus fractions and seedling growth in soils from a Wyoming lodgepole pine forest. *Forest Ecology and Management*, **140**, 19-28.

Gill, R. & Beardall, V. (2001) The impact of deer on woodlands: the effects of browsing and seed dispersal on vegetation structure and composition. *Forestry*, **74**, 209-218.

Groengroeft, A., de Blécourt, M., Classen, N., Landschreiber , L., and Eschenbach, A. (2018) Acacia trees modify soil water dynamics and the potential groundwater recharge in savanna ecosystems. This volume.

Guyette, R.P., Muzika, R.-M. & Dey, D.C. (2002) Dynamics of an anthropogenic fire regime. *Ecosystems*, **5**, 472-486.

Hackmann, T. & Spain, J. (2010) Invited review: Ruminant ecology and evolution: Perspectives useful to ruminant livestock research and production. *Journal of Dairy Science*, **93**, 1320-1334.

Hahn, B., Richardson, F., Hoffman, M., Roberts, R., Todd, S. & Carrick, P. (2005) A simulation model of long-term climate, livestock and vegetation interactions on communal rangelands in the semi-arid Succulent Karoo, Namaqualand, South Africa. *Ecological Modelling*, **183**, 211-230.

Harris, A., Carr, A. & Dash, J. (2014) Remote sensing of vegetation cover dynamics and resilience across southern Africa. *International Journal of Applied Earth Observation and Geoinformation*, **28**, 131-139.

Hobbs, N.T. & Schimel, D.S. (1984) Fire effects on nitrogen mineralization and fixation in mountain shrub and grassland communities. *Journal of Range Management*, 402-405.

Hülber, K., Ertl, S., Gottfried, M., Reiter, K. & Grabherr, G. (2005) Gourmets or gourmands?—Diet selection by large ungulates in high-alpine plant communities and possible impacts on plant propagation. *Basic and Applied Ecology*, **6**, 1-10.

Iason, G.R., Dicke, M. & Hartley, S.E. (2012) *The ecology of plant secondary metabolites: from genes to global processes*. Cambridge University Press.

Joubert, D., Rothauge, A. & Smit, G. (2008) A conceptual model of vegetation dynamics in the semiarid Highland savanna of Namibia, with particular reference to bush thickening by Acacia mellifera. *Journal of Arid environments*, **72**, 2201-2210.

Joubert, D., Smit, G. & Hoffman, M. (2012) The role of fire in preventing transitions from a grass dominated state to a bush thickened state in arid savannas. *Journal of Arid Environments*, **87**, 1-7.

Joubert, D.F., Stolter, C., Krewenka, K.M., Uunona ,N., Amputu, V., Nghalipo, E., Thompson, A., Schütte, K., Kruspe, M., Throop, H., du Preez, P., Beytell, P., le Roux, M. & Aindongo, H. (2018) Impacts of fire history in a semiarid woodland savanna. This volume.

Jürgens, N., Schmiedel, U. & Hoffman. M.T. (2010). Biodiversity in southern Africa. Volume 1. Klaus Hess Publishers, Göttingen & Windhoek.

Jürgens, N., Strohbach, B., Lages, F., Schmiedel, U., Finckh, M., Sichone, P., Marie Hahn, L.-M. & Zigelski, P. (2018) Biodiversity Observation – an overview of the current state and first results of biodiversity monitoring studies. This volume.

Kier, G., Mutke, J., Dinerstein, E., Ricketts, T.H., Kuper, W., Kreft, H. & Barthlott, W. (2005) Global patterns of plant diversity and floristic knowledge. *Journal of Biogeography*, **32**, 1107-1116.

Knicker, H. (2007) How does fire affect the nature and stability of soil organic nitrogen and carbon? A review. *Biogeochemistry*, **85**, 91-118.

Knox, N.M., Skidmore, A.K., Prins, H.H., Heitkönig, I.M., Slotow, R., van der Waal, C. & de Boer, W.F. (2012) Remote sensing of forage nutrients: Combining ecological and spectral absorption feature data. *ISPRS Journal of Photogrammetry and Remote Sensing*, **72**, 27-35.

Le Roux, P.J., Müller, M., Curtis, B. & Mannheimer, C. (2009) *Le Roux and Müller's field guide to the trees & shrubs of Namibia*. Macmillan Education Namibia.

Lehmann, C.E.R., Ratnam, J. & Hutley, L.B. (2009) Which of these continents is not like the other? Comparisons of tropical savanna systems: key questions and challenges. *New Phytologist*, **181**, 508-511.

Madibela, O. R., Kemiso, D. & Kwedibana, J. (2018) Quality of wild herbaceous legumes and its role in livestock nutrition. This volume.

McKiernan, A.B., Hovenden, M.J., Brodribb, T.J., Potts, B.M., Davies, N.W. & O'Reilly-Wapstra, J.M. (2014) Effect of limited water availability on foliar plant secondary metabolites of two Eucalyptus species. *Environmental and Experimental Botany*, **105**, 55-64.

McNaughton, S., Ruess, R. & Seagle, S. (1988) Large mammals and process dynamics in African ecosystems. *BioScience*, **38**, 794-800.

Murphy, B.P., Andersen, A.N. & Parr, C.L. (2016) The underestimated biodiversity of tropical grassy biomes. *Philosophical Transactions of the Royal Society B*, **371**, 20150319.

Mutanga, O. & Skidmore, A. (2004) Integrating imaging spectroscopy and neural networks to map grass quality in the Kruger National Park, South Africa. *Remote Sensing of Environment*, **90**, 104-115.

Mutanga, O. & Skidmore, A.K. (2007) Red edge shift and biochemical content in grass canopies. *ISPRS journal of Photogrammetry and Remote Sensing*, **62**, 34-42.

Naidoo, S., Davis, C. & Van Garderen, E.A. (2013) Forests, rangelands and climate change in southern Africa. *Forests and Climate Change Working Paper*,

O'Connor, T.G., Puttick, J.R. & Hoffman, M.T. (2014) Bush encroachment in southern Africa: changes and causes. *African Journal of Range & Forage Science*, **31**, 67-88.

Ojima, D.S., Schimel, D., Parton, W. & Owensby, C. (1994) Long-and short-term effects of fire on nitrogen cycling in tallgrass prairie. *Biogeochemistry*, **24**, 67-84.

Olff, H. & Ritchie, M.E. (1998) Effects of herbivores on grassland plant diversity. *Trends in Ecology & Evolution*, **13**, 261-265.

Olivier, G., Helmschrot, J. & W.P. de Clercq (2018) Are large classical gully systems inactive remnants of the past – a field based case study investigating sediment movement. This volume.

Palmer, T. 2003. Rangeland resources: South Africa, Namibia, Botswana, Lesotho, Swaziland, Zimbabwe. Booklet prepared for delegates to the VII International Rangeland Congress, Durban, South Africa (FAFO and ARC Range and Forage Institute).

Palmer, A.R. & Bennett, J.E. (2013) Degradation of communal rangelands in South Africa: towards an improved understanding to inform policy. *African Journal of Range & Forage Science*, **30**, 57-63.

Pastor, J. & Naiman, R.J. (1992) Selective foraging and ecosystem processes in boreal forests. *American Naturalist*, 690-705.

Pringle, H., Zimmerman, I., Tinley, K., 2011. Accelerating landscape incision and the downward spiralling rain use efficiency of Namibian rangelands. Agricola **21**, 43-52.

Prothero, D.R. & Foss, S.E. (2007) *The evolution of artiodactyls*. JHU Press.

Ramoelo, A., Cho, M., Mathieu, R. & Skidmore, A.K. (2015a) Potential of Sentinel-2 spectral configuration to assess rangeland quality. *Journal of Applied Remote Sensing*, **9**, 094096-094096.

Ramoelo, A., Skidmore, A.K., Cho, M.A., Schlerf, M., Mathieu, R. & Heitkönig, I.M. (2012) Regional estimation of savanna grass nitrogen using the red-edge band of the spaceborne RapidEye sensor. *International Journal of Applied Earth Observation and Geoinformation*, **19**, 151-162.

Ramoelo, A., Cho, M.A., Mathieu, R., Madonsela, S., Van De Kerchove, R., Kaszta, Z. & Wolff, E. (2015b) Monitoring grass nutrients and biomass as indicators of rangeland quality and quantity using random forest modelling and WorldView-2 data. *International Journal of Applied Earth Observation and Geoinformation*, **43**, 43-54.

Ramoelo, A., Skidmore, A., Cho, M.A., Mathieu, R., Heitkönig, I., Dudeni-Tlhone, N., Schlerf, M. & Prins, H. (2013) Non-linear partial least square regression increases the estimation accuracy of grass nitrogen and phosphorus using in situ hyperspectral and environmental data. *ISPRS Journal of Photogrammetry and Remote Sensing*, **82**, 27-40.

Ratnam, J., Bond, W.J., Fensham, R.J., Hoffmann, W.A., Archibald, S., Lehmann, C.E.R., Anderson, M.T., Higgins, S.I. & Sankaran, M. (2011) When is a 'forest' a savanna, and why does it matter? *Global Ecology and Biogeography*, **20**, 653-660.

Rieske, L., Housman, H. & Arthur, M. (2002) Effects of prescribed fire on canopy foliar chemistry and suitability for an insect herbivore. *Forest Ecology and Management*, **160**, 177-187.

Rooney, T.P. (2001) Deer impacts on forest ecosystems: a North American perspective. *Forestry*, **74**, 201-208.

Rouse, J., Haas, R., Schell, J., Deering, D. & Harlan, J. (1974) Monitoring the vernal advancement of retrogradation of natural vegetation, NASA/GSFC, Type III, Final Report. *Greenbelt, MD*,

Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gaye, C.B., Edmunds, W.M. & Simmers, I. (2006) Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes*, **20**, 3335-3370.

Scholes, R. & Archer, S. (1997) Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics*, **28**, 517-544.

Schucknecht, A., Meroni, M., Kayitakire, F. & Boureima, A. (2017) Phenology-Based Biomass Estimation to Support Rangeland Management in Semi-Arid Environments. *Remote Sensing*, **9**, 463.

Skidmore, A.K., Ferwerda, J.G., Mutanga, O., Van Wieren, S.E., Peel, M., Grant, R.C., Prins, H.H., Balcik, F.B. & Venus, V. (2010) Forage quality of savannas—Simultaneously mapping foliar protein and polyphenols for trees and grass using hyperspectral imagery. *Remote Sensing of Environment*, **114**, 64-72.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V. & de Haan, C. (2006) *Livestock's long shadow: environmental issues and options*. Food & Agriculture Org.

Stolter, C. (2008) Intra-individual plant response to moose brwosing: Feedback loops and impacts on multiple consumers. *Ecological Monographs*, **78**, 167-183.

Stolter, C., Ball, J.P. & Julkunen-Tiitto, R. (2013) Seasonal differences in the relative importance of specific phenolics and twig morphology result in contrasting patterns of foraging by a generalist herbivore. *Canadian Journal of Zoology*, **91**, 338-347.

Stolter, C., Ball, J.P., Niemelä, P. & Julkunen-Tiitto, R. (2010) Herbivores and variation in the composition of specific phenolics of boreal coniferous trees: a search for patterns. *Chemoecology*, **20**, 229-242.

Stolter, C., Ball, J.P., Julkunen-Tiitto, R., Lieberei, R. & Ganzhorn, J.U. (2005) Winter browsing of moose on two different willow species: food selection in relation to plant chemistry and plant response. *Canadian Journal of Zoology*, **83**, 807-819.

Stolter, C., Ramoelo, A., Kesch, K., Madibela, O., Cho, M.A. & Joubert, D. (2018a) Forage quality and availability for large herbivores. This volume.

Stolter, C., Joubert, D., Schwarz, K. & Finckh, M. (2018b) Bush encroachment management and its impact on plants and large herbivores. This volume

Stolter, C. (2018a) Open-access database on nutritional quality of food plants for herbivores. This volume.

Stolter, C. (2018b) What is quality for a ruminant? A short introduction to the meaning of plant chemical composition measurements. This volume.

Tambo G.V.; Els W.N.; Neil H.S.; Barnard J.F. Morgan J. 2017. Effects of drought on the South African Agriculture, *International Journal of Agricultural Economics and Extension*, **5(3),** 226 – 276

Tegelberg, R., Veteli, T., Aphalo, P.J. & Julkunen-Tiitto, R. (2003) Clonal differences in growth and phenolics of willows exposed to elevated ultraviolet-B radiation. *Basic and Applied Ecology*, **4**, 219-228.

Thornton, P.K. (2010) Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **365**, 2853-2867.

Turpie, J.K. & Crowe, T.M. (1994) Patterns of Distribution, Diversity and Endemism of Larger African Mammals. *South African Journal of Zoology*, **29**, 19-32.

Úbeda, X., Lorca, M., Outeiro, L.R., Bernia, S. & Castellnou, M. (2005) Effects of prescribed fire on soil quality in Mediterranean grassland (Prades Mountains, north-east Spain). *International Journal of Wildland Fire*, **14**, 379-384.

United Nations, Department of Economic and Social Affairs, Population Division -UNPD 2015. World Population Prospects: The 2015 Revision, Methodology of the United Nations Population Estimates and Projections. ESA/P/WP.242.

Van de Vijver, C., Poot, P. & Prins, H. (1999) Causes of increased nutrient concentrations in post-fire regrowth in an East African savanna. *Plant and Soil*, **214**, 173-185.

Van der Wal, R., van Lieshout, S.M. & Loonen, M.J. (2001) Herbivore impact on moss depth, soil temperature and arctic plant growth. *Polar Biology*, **24**, 29-32.

Villalba, J.J., Provenza, F.D. & Bryant, J. (2002) Consequences of the interaction between nutrients and plant secondary metabolites on herbivore selectivity: benefits or detriments for plants? *Oikos*, **97**, 282-292.

Wardle, D.A., Bardgett, R.D., Klironomos, J.N., Setälä, H., Van Der Putten, W.H. & Wall, D.H. (2004) Ecological linkages between aboveground and belowground biota. *Science*, **304**, 1629-1633.

Zimmermann, I., Pringle, H., Madibela, O. & Kahl, U (2018) Initial experiments on intensified use of rangelands through enhanced water and nutrient cycling. This volume.

References [CrossRef]

Archibald, S., Bond, W., Stock, W. & Fairbanks, D. (2005) Shaping the landscape: fire–grazer interactions in an African savanna. *Ecological Applications*, **15**, 96-109. CrossRef

Backéus, I. (1992) Distribution and vegetation dynamics of humid savannas in Africa and Asia. *Journal of Vegetation Science*, **3**, 345-356. CrossRef

Barthlott, W., Hostert, A., Kier, G., Koper, W., Kreft, H., Mutke, J., Rafiqpoor, M.D. & Sommer, J.H. (2007) Geographic patterns of vascular plant diversity at continental to global scales. *Erdkunde*, **61**, 305-315. CrossRef

Benthien, O., Bober, J., Castens, J. & Stolter, C. (2016) Seed dispersal capacity of sheep and goats in a near-coastal dry grassland habitat. *Basic and Applied Ecology*, **17**, 508-515. CrossRef

Bird, M. & Cali, J. (1998) A million-year record of fire in sub-Saharan Africa. *Nature*, **394**, 767-769. CrossRef

Bobrowski, M., Gillich, B. & Stolter, C. (2015) Modelling browsing of deer on beech and birch in northern Germany. *Forest Ecology and Management*, **358**, 212-221. CrossRef

Bond, W., Midgley, G. & Woodward, F. (2003) The importance of low atmospheric CO2 and fire in promoting the spread of grasslands and savannas. *Global Change Biology*, **9**, 973-982. CrossRef

Bond, W.J. & van Wilgen, B.W. (1996) Why and how do ecosystems burn? *Fire and Plants*, pp. 16-33. Springer.

Bond, W.J. & Keeley, J.E. (2005) Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems. *Trends in Ecology & Evolution*, **20**, 387-394. CrossRef

Child, R.D. & Frasler, G. (1992) ARS range research. *Rangelands Archives*, **14**, 17-32.

Cho, M.A. & Skidmore, A.K. (2006) A new technique for extracting the red edge position from hyperspectral data: The linear extrapolation method. *Remote Sensing of Environment*, **101**, 181-193. CrossRef

Christian, C. (2010) Desk top Study on the Effect of Bush Encroachment on Groundwater Resources in Namibia. Pages 109 and Appendix. Colin Christian & Associates CC, Windhoek.

Craggs, G. 2017. Rangelands: Critical to the environment and under constant threat. Future Directions International. Dalkeith, Australia. http://www.futuredirections.org.au/publication/rangelands-critical-environment-constant-threat/ (Accessed on the 30 July 2017).

Cumming, D.H. & Cumming, G.S. (2003) Ungulate community structure and ecological processes: body size, hoof area and trampling in African savannas. *Oecologia*, **134**, 560-568. CrossRef

Curran, P.J., Dungan, J.L., Macler, B.A. & Plummer, S.E. (1991) The effect of a red leaf pigment on the relationship between red edge and chlorophyll concentration. *Remote Sensing of Environment*, **35**, 69-76. CrossRef

FAO (Food and Agriculture Organization of the United Nations). 2010. Land degradation assessment in drylands (LADA): http://www.fao.org/nr/lada/ (accessed April 2017).

Giardina, C.P. & Rhoades, C.C. (2001) Clear cutting and burning affect nitrogen supply, phosphorus fractions and seedling growth in soils from a Wyoming lodgepole pine forest. *Forest Ecology and Management*, **140**, 19-28. CrossRef

Gill, R. & Beardall, V. (2001) The impact of deer on woodlands: the effects of browsing and seed dispersal on vegetation structure and composition. *Forestry*, **74**, 209-218. CrossRef

Groengroeft, A., de Blécourt, M., Classen, N., Landschreiber , L., and Eschenbach, A. (2018) Acacia trees modify soil water dynamics and the potential groundwater recharge in savanna ecosystems. This volume. CrossRef

Guyette, R.P., Muzika, R.-M. & Dey, D.C. (2002) Dynamics of an anthropogenic fire regime. *Ecosystems*, **5**, 472-486.

Hackmann, T. & Spain, J. (2010) Invited review: Ruminant ecology and evolution: Perspectives useful to ruminant livestock research and production. *Journal of Dairy Science*, **93**, 1320-1334. CrossRef

Hahn, B., Richardson, F., Hoffman, M., Roberts, R., Todd, S. & Carrick, P. (2005) A simulation model of long-term climate, livestock and vegetation interactions on communal rangelands in the semi-arid Succulent Karoo, Namaqualand, South Africa. *Ecological Modelling*, **183**, 211-230. CrossRef

Harris, A., Carr, A. & Dash, J. (2014) Remote sensing of vegetation cover dynamics and resilience across southern Africa. *International Journal of Applied Earth Observation and Geoinformation*, **28**, 131-139. CrossRef

Hobbs, N.T. & Schimel, D.S. (1984) Fire effects on nitrogen mineralization and fixation in mountain shrub and grassland communities. *Journal of Range Management*, 402-405. CrossRef

Hülber, K., Ertl, S., Gottfried, M., Reiter, K. & Grabherr, G. (2005) Gourmets or gourmands?—Diet selection by large ungulates in high-alpine plant communities and possible impacts on plant propagation. *Basic and Applied Ecology*, **6**, 1-10. CrossRef

Iason, G.R., Dicke, M. & Hartley, S.E. (2012) *The ecology of plant secondary metabolites: from genes to global processes*. Cambridge University Press. CrossRef

Joubert, D., Rothauge, A. & Smit, G. (2008) A conceptual model of vegetation dynamics in the semiarid Highland savanna of Namibia, with particular reference to bush thickening by Acacia mellifera. *Journal of Arid environments*, **72**, 2201-2210. CrossRef

Joubert, D., Smit, G. & Hoffman, M. (2012) The role of fire in preventing transitions from a grass dominated state to a bush thickened state in arid savannas. *Journal of Arid Environments*, **87**, 1-7. CrossRef

Joubert, D.F., Stolter, C., Krewenka, K.M., Uunona ,N., Amputu, V., Nghalipo, E., Thompson, A., Schütte, K., Kruspe, M., Throop, H., du Preez, P., Beytell, P., le Roux, M. & Aindongo, H. (2018) Impacts of fire history in a semiarid woodland savanna. This volume. CrossRef

Jürgens, N., Schmiedel, U. & Hoffman. M.T. (2010). Biodiversity in southern Africa. Volume 1. Klaus Hess Publishers, Göttingen & Windhoek.

Jürgens, N., Strohbach, B., Lages, F., Schmiedel, U., Finckh, M., Sichone, P., Marie Hahn, L.-M. & Zigelski, P. (2018) Biodiversity Observation – an overview of the current state and first results of biodiversity monitoring studies. This volume. CrossRef

Kier, G., Mutke, J., Dinerstein, E., Ricketts, T.H., Kuper, W., Kreft, H. & Barthlott, W. (2005) Global patterns of plant diversity and floristic knowledge. *Journal of Biogeography*, **32**, 1107-1116. CrossRef

Knicker, H. (2007) How does fire affect the nature and stability of soil organic nitrogen and carbon? A review. *Biogeochemistry*, **85**, 91-118. CrossRef

Knox, N.M., Skidmore, A.K., Prins, H.H., Heitkönig, I.M., Slotow, R., van der Waal, C. & de Boer, W.F. (2012) Remote sensing of forage nutrients: Combining ecological and spectral absorption feature data. *ISPRS Journal of Photogrammetry and Remote Sensing*, **72**, 27-35. CrossRef

Le Roux, P.J., Müller, M., Curtis, B. & Mannheimer, C. (2009) *Le Roux and Müller's field guide to the trees & shrubs of Namibia*. Macmillan Education Namibia.

Lehmann, C.E.R., Ratnam, J. & Hutley, L.B. (2009) Which of these continents is not like the other? Comparisons of tropical savanna systems: key questions and challenges. *New Phytologist*, **181**, 508-511. CrossRef

Madibela, O. R., Kemiso, D. & Kwedibana, J. (2018) Quality of wild herbaceous legumes and its role in livestock nutrition. This volume. CrossRef

McKiernan, A.B., Hovenden, M.J., Brodribb, T.J., Potts, B.M., Davies, N.W. & O'Reilly-Wapstra, J.M. (2014) Effect of limited water availability on foliar plant secondary metabolites of two Eucalyptus species. *Environmental and Experimental Botany*, **105**, 55-64. CrossRef

McNaughton, S., Ruess, R. & Seagle, S. (1988) Large mammals and process dynamics in

African ecosystems. *BioScience*, **38**, 794-800. CrossRef
Murphy, B.P., Andersen, A.N. & Parr, C.L. (2016) The underestimated biodiversity of tropical grassy biomes. *Philosophical Transactions of the Royal Society B*, **371**, 20150319. CrossRef
Mutanga, O. & Skidmore, A. (2004) Integrating imaging spectroscopy and neural networks to map grass quality in the Kruger National Park, South Africa. *Remote Sensing of Environment*, **90**, 104-115. CrossRef
Mutanga, O. & Skidmore, A.K. (2007) Red edge shift and biochemical content in grass canopies. *ISPRS journal of Photogrammetry and Remote Sensing*, **62**, 34-42. CrossRef
Naidoo, S., Davis, C. & Van Garderen, E.A. (2013) Forests, rangelands and climate change in southern Africa. *Forests and Climate Change Working Paper*,
O'Connor, T.G., Puttick, J.R. & Hoffman, M.T. (2014) Bush encroachment in southern Africa: changes and causes. *African Journal of Range & Forage Science*, **31**, 67-88. CrossRef
Ojima, D.S., Schimel, D., Parton, W. & Owensby, C. (1994) Long-and short-term effects of fire on nitrogen cycling in tallgrass prairie. *Biogeochemistry*, **24**, 67-84. CrossRef
Olff, H. & Ritchie, M.E. (1998) Effects of herbivores on grassland plant diversity. *Trends in Ecology & Evolution*, **13**, 261-265. CrossRef
Olivier, G., Helmschrot, J. & W.P. de Clercq (2018) Are large classical gully systems inactive remnants of the past – a field based case study investigating sediment movement. This volume.
Palmer, T. 2003. Rangeland resources: South Africa, Namibia, Botswana, Lesotho, Swaziland, Zimbabwe. Booklet prepared for delegates to the VII International Rangeland Congress, Durban, South Africa (FAFO and ARC Range and Forage Institute).
Palmer, A.R. & Bennett, J.E. (2013) Degradation of communal rangelands in South Africa: towards an improved understanding to inform policy. *African Journal of Range & Forage Science*, **30**, 57-63. CrossRef
Pastor, J. & Naiman, R.J. (1992) Selective foraging and ecosystem processes in boreal forests. *American Naturalist*, 690-705. CrossRef
Pringle, H., Zimmerman, I., Tinley, K., 2011. Accelerating landscape incision and the downward spiralling rain use efficiency of Namibian rangelands. Agricola **21**, 43-52.
Prothero, D.R. & Foss, S.E. (2007) *The evolution of artiodactyls*. JHU Press.
Ramoelo, A., Cho, M., Mathieu, R. & Skidmore, A.K. (2015a) Potential of Sentinel-2 spectral configuration to assess rangeland quality. *Journal of Applied Remote Sensing*, **9**, 094096-094096.
Ramoelo, A., Skidmore, A.K., Cho, M.A., Schlerf, M., Mathieu, R. & Heitkönig, I.M. (2012) Regional estimation of savanna grass nitrogen using the red-edge band of the spaceborne RapidEye sensor. *International Journal of Applied Earth Observation and Geoinformation*, **19**, 151-162. CrossRef
Ramoelo, A., Cho, M.A., Mathieu, R., Madonsela, S., Van De Kerchove, R., Kaszta, Z. & Wolff, E. (2015b) Monitoring grass nutrients and biomass as indicators of rangeland quality and quantity using random forest modelling and WorldView-2 data. *International Journal of Applied Earth Observation and Geoinformation*, **43**, 43-54. CrossRef
Ramoelo, A., Skidmore, A., Cho, M.A., Mathieu, R., Heitkönig, I., Dudeni-Tlhone, N., Schlerf, M. & Prins, H. (2013) Non-linear partial least square regression increases the estimation accuracy of grass nitrogen and phosphorus using in situ hyperspectral and environmental data. *ISPRS Journal of Photogrammetry and Remote Sensing*, **82**, 27-40. CrossRef
Ratnam, J., Bond, W.J., Fensham, R.J., Hoffmann, W.A., Archibald, S., Lehmann, C.E.R., Anderson, M.T., Higgins, S.I. & Sankaran, M. (2011) When is a 'forest' a savanna, and why does it matter? *Global Ecology and Biogeography*, **20**, 653-660. CrossRef
Rieske, L., Housman, H. & Arthur, M. (2002) Effects of prescribed fire on canopy foliar chemistry and suitability for an insect herbivore. *Forest Ecology and Management*, **160**, 177-187. CrossRef
Rooney, T.P. (2001) Deer impacts on forest ecosystems: a North American perspective. *Forestry*, **74**, 201-208. CrossRef
Rouse, J., Haas, R., Schell, J., Deering, D. & Harlan, J. (1974) Monitoring the vernal advancement of retrogradation of natural vegetation, NASA/GSFC, Type III, Final Report. *Greenbelt, MD*,
Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gaye, C.B., Edmunds, W.M. & Simmers, I. (2006) Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes*, **20**, 3335-3370. CrossRef
Scholes, R. & Archer, S. (1997) Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics*, **28**, 517-544. CrossRef
Schucknecht, A., Meroni, M., Kayitakire, F. & Boureima, A. (2017) Phenology-Based Biomass Estimation to Support Rangeland Management in Semi-Arid Environments. *Remote Sensing*, **9**, 463. CrossRef
Skidmore, A.K., Ferwerda, J.G., Mutanga, O., Van Wieren, S.E., Peel, M., Grant, R.C., Prins, H.H., Balcik, F.B. & Venus, V. (2010) Forage quality of savannas—Simultaneously mapping foliar protein and polyphenols for trees and grass using hyperspectral imagery. *Remote Sensing of Environment*, **114**, 64-72. CrossRef
Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V. & de Haan, C. (2006) *Livestock's long shadow: environmental issues and options*. Food & Agriculture Org.
Stolter, C. (2008) Intra-individual plant response to moose brwosing: Feedback loops and impacts on multiple consumers. *Ecological Monographs*, **78**, 167-183. CrossRef
Stolter, C., Ball, J.P. & Julkunen-Tiitto, R. (2013) Seasonal differences in the relative importance of specific phenolics and twig morphology result in contrasting patterns of foraging by a generalist herbivore. *Canadian Journal of Zoology*, **91**, 338-347. CrossRef
Stolter, C., Ball, J.P., Niemelä, P. & Julkunen-Tiitto, R. (2010) Herbivores and variation in the composition of specific phenolics of boreal coniferous trees: a search for patterns. *Chemoecology*, **20**, 229-242. CrossRef
Stolter, C., Ball, J.P., Julkunen-Tiitto, R., Lieberei, R. & Ganzhorn, J.U. (2005) Winter browsing of moose on two different willow species: food selection in relation to plant chemistry and plant response. *Canadian Journal of Zoology*, **83**, 807-819. CrossRef
Stolter, C., Ramoelo, A., Kesch, K., Madibela, O., Cho, M.A. & Joubert, D. (2018a) Forage quality and availability for large herbivores. This volume. CrossRef
Stolter, C., Joubert, D., Schwarz, K. & Finckh, M. (2018b) Bush encroachment management and its impact on plants and large herbivores. This volume. CrossRef
Stolter, C. (2018a) Open-access database on nutritional quality of food plants for herbivores. This volume. CrossRef
Stolter, C. (2018b) What is quality for a ruminant? A short introduction to the meaning of plant chemical composition measurements. This volume. CrossRef
Tambo G.V.; Els W.N.; Neil H.S.; Barnard J.F. Morgan J. 2017. Effects of drought on the South African Agriculture, *International Journal of Agricultural Economics and Extension*, **5(3),** 226 – 276
Tegelberg, R., Veteli, T., Aphalo, P.J. & Julkunen-Tiitto, R. (2003) Clonal differences in growth and phenolics of willows exposed to elevated ultraviolet-B radiation. *Basic and Applied Ecology*, **4**, 219-228. CrossRef
Thornton, P.K. (2010) Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **365**, 2853-2867. CrossRef
Turpie, J.K. & Crowe, T.M. (1994) Patterns of Distribution, Diversity and Endemism of Larger African Mammals. *South African Journal of Zoology*, **29**, 19-32. CrossRef
Úbeda, X., Lorca, M., Outeiro, L.R., Bernia, S. & Castellnou, M. (2005) Effects of prescribed fire on soil quality in Mediterranean grassland (Prades Mountains,

north-east Spain). *International Journal of Wildland Fire*, **14**, 379-384. CrossRef

United Nations, Department of Economic and Social Affairs, Population Division -UNPD 2015. World Population Prospects: The 2015 Revision, Methodology of the United Nations Population Estimates and Projections. ESA/P/WP.242.

Van de Vijver, C., Poot, P. & Prins, H. (1999) Causes of increased nutrient concentrations in post-fire regrowth in an East African savanna. *Plant and Soil*, **214**, 173-185. CrossRef

Van der Wal, R., van Lieshout, S.M. & Loonen, M.J. (2001) Herbivore impact on moss depth, soil temperature and arctic plant growth. *Polar Biology*, **24**, 29-32. CrossRef

Villalba, J.J., Provenza, F.D. & Bryant, J. (2002) Consequences of the interaction between nutrients and plant secondary metabolites on herbivore selectivity: benefits or detriments for plants? *Oikos*, **97**, 282-292. CrossRef

Wardle, D.A., Bardgett, R.D., Klironomos, J.N., Setälä, H., Van Der Putten, W.H. & Wall, D.H. (2004) Ecological linkages between aboveground and belowground biota. *Science*, **304**, 1629-1633. CrossRef

Zimmermann, I., Pringle, H., Madibela, O. & Kahl, U (2018) Initial experiments on intensified use of rangelands through enhanced water and nutrient cycling. This volume. CrossRef

Acacia trees modify soil water dynamics and the potential groundwater recharge in savanna ecosystems

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Abstract: The effect of increasing tree density on groundwater resources of semiarid landscapes is a topic of controversy. Since 2007, we have registered the soil water dynamics with field monitoring techniques on a commercial rangeland farm in the central Namibian thorn-bush savanna. Monitoring profiles are located below *Acacia mellifera* canopies, in the intercanopy area, and on a de-bushed grassland. Here we demonstrate (1) an increase in soil moisture larger than precipitation at some rain events, interpreted as water run-on resulting from surface ponding; (2) an overall reduction in water infiltration in the below-canopy area of *A. mellifera* compared to the intercanopy space; and (3) a faster drying of the soil in the below-canopy space because of root water uptake. These processes resulted in a potential for deep drainage about threefold larger in the intercanopy space than in the area below the canopy. Thus, increasing bush encroachment is likely to reduce groundwater recharge and should be validated by an interdisciplinary analysis of hydrogeologists, soil scientists, botanists, and farm managers.

Resumo: É controversamente discutido o efeito do aumento da densidade de árvores nos recursos de águas subterrâneas de paisagens semi-áridas. Desde 2007 que registamos as dinâmicas da água no solo, com técnicas de monitorização de campo, numa quinta comercial de pastagens localizada na savana espinhosa da Namíbia central. Perfis de monitorização estão localizados sob copas de *Acacia mellifera*, na área entre copas, e numa pastagem sem vegetação. Aqui demonstramos i) um aumento na humidade do solo maior que a precipitação em alguns eventos de chuva, interpretada como a infiltração de água resultante da sua acumulação à superfície, ii) no total uma reduzida infiltração de água na área abaixo da copa de *A. mellifera*, em comparação com o espaço entre copas, e iii) uma secagem mais rápida do solo no espaço abaixo das copas, devido à captação de água pelas raízes. Estes processos resultaram num potencial de drenagem profundo, cerca de três vezes maior no espaço entre copas que na área abaixo das mesmas. Desta forma, a expansão da invasão do mato poderá reduzir a recarga das águas subterrâneas, devendo ser confirmada por uma análise interdisciplinar de hidrogeólogos, cientistas do solo, botanistas e gestores de quintas.

Introduction

The change in vegetation cover of African savannas, with an increasing abundancy of woody species, is a widely observed phenomenon known as "bush encroachment". The causes are a subject of debate (Archer, 2010; Briggs et al., 2005; de Klerk, 2004; Eldridge et al., 2011; O'Connor et al., 2014; Van Auken, 2000; Ward, 2005), and neither measures to prevent bush thickening nor generally accepted economic and sustainable strategies to reduce bush coverage have yet been found. The encroachment of bushes has substantial economic impacts on the rangeland farmers, as the capacity of the grazing grounds for livestock is being reduced. The number of livestock in bush-encroached rangelands has thus become much smaller compared to in earlier periods of rangeland management; for example, on commercial farms in Namibia, livestock numbers have decreased since the late 1950s to 36% (de Klerk, 2004).

There has been a long debate about the differences in water consumption of trees and grasses in savanna ecosystems, the competition for water between the two vegetation types in different environmental settings, and the consequences of bush encroachment on water balances and especially groundwater recharge (e.g., O'Connor et al., 2014; Scanlon et al., 2006; Scholes & Archer, 1997). Reviewing the literature on the hydrogeological role of trees in water-limited environments, Lubczynski (2009) summarized that the survival strategy of trees in these systems is typically based on rooting systems that allow water uptake directly from the groundwater or the capillary fringe. For the southern African rangelands, with their widespread bush encroachment, robust information about the interaction of bushes and trees on the one hand and the low layer of grasses, herbs, and dwarf shrubs on the other hand on the water dynamics is limited (Christian, 2010). Thus, SASSCAL studied these interactions with different methodological approaches.

We observed the soil water dynamics of both bush-encroached and debushed areas starting in 2007, using field monitoring techniques on a commercial rangeland farm in the central Namibian thorn-bush savanna, and since 2014 on two additional farms (east of Otjiwarongo, northeast of Grootfontein). The research aimed to understand the influence of different vegetation covers (tree cover versus grass cover) on the processes of infiltration, evapotranspiration, and groundwater recharge. Although groundwater recharge cannot be measured directly (Kinzelbach et al., 2002), the field measurements allow quantification of the number of days per year when deep percolation is physically possible, and thus allow an interpretation of the data with regard to the likelihood of groundwater recharge under various vegetation covers.

Figure 1: Plot EL (12/3/2011); the arrows show the location of the soil profiles “intercanopy” (left) and “below-canopy” (right).

Methods

Study area

The study area is located on a commercial rangeland farm in central Namibia (Otjozondjupa region) about 110 km north of Windhoek. The climate (type BWh, according to Koeppen) is characterized by summer rainfall (predominantly between December and April) with mean annual precipitation of 413 mm (data from local climate station, 2001–2014). Intense rain events often combined with thunderstorms are typical. The high temperature and low humidity lead to a potential evaporation rate of 1,820 mm a^{-1} (Mendelsohn et al., 2009). The topography of the area is almost flat; the altitude, about 1,500 m above sea level. A net of ephemeral river systems of the Omatako catchment drain the farm to the northeast. In the rainy season, the run-off water is retained in dams and swales along the rivers.

On the farm, we monitored soil water dynamics at the two profiles at plots EL (21.654°S/16.686°E) and ES (21.611°S/16.870°E), situated in bush-encroached areas, and at plot EG (21.612°S/16.903°E), located in an area that had been cleared of trees and shrubs. EL was characterized by patches of old *Acacia* trees (Fig. 1) and had a total coverage of shrubs and trees of 12%. ES has a few medium-sized *Acacia* bushes, and the coverage of trees and shrubs is 4.4%. EG was cleared of trees and shrubs by chopping in 2009, and subsequently the soil surface has been ploughed and planted with grasses. EL and ES had a flat terrain, whereas EG was situated in a slight depression. The soils at the studied plots were chromic luvisols; the texture was sandy loam or sandy clay loam for the topsoil, with increasing clay content with depth. With a topsoil pH of 5.1 to 5.5 and low amounts of silt, the soils had low aggregate stability and tended to form surface crusts. At about 1 m depth, the red soil material covered a thin layer of saprolite composed of the bedrock, which is dominated by granites of the Damara granite intrusion. Groundwater depth is about 70 m below the soil surface. Further details on soil properties are provided by Petersen (2008).

Soil water monitoring

Each plot consisted of two instrumented soil profiles. At the bush-encroached plots, one soil profile was situated under a tree canopy and the other soil profile was situated in an intercanopy patch without tree coverage. Both soil profiles at the EG plot were covered with grass, and a tree canopy was absent. The distance between both instrumented soil profiles at each plot was about 5 m.

Soil water content (SWC, % volume) in each profile was monitored using TDR sensors (Easytest type FP/mts, Institute of Agrophysics, Poland) with 100 mm rod length, installed horizontally from an open pit at depths of 20, 40, 60 and 80 cm below soil surface, and which were connected to a logger (type TDR/MUX/mts). The daily measuring interval was fixed at 8:00, 16:00, and 24:00 hours. The sensors additionally recorded the soil temperature.

Soil water storage (SWS, mm) for each profile (1 m depth) was calculated from SWC by taking the respective depth intervals of the four sensors into account. Soil water potential (SWP, pF)

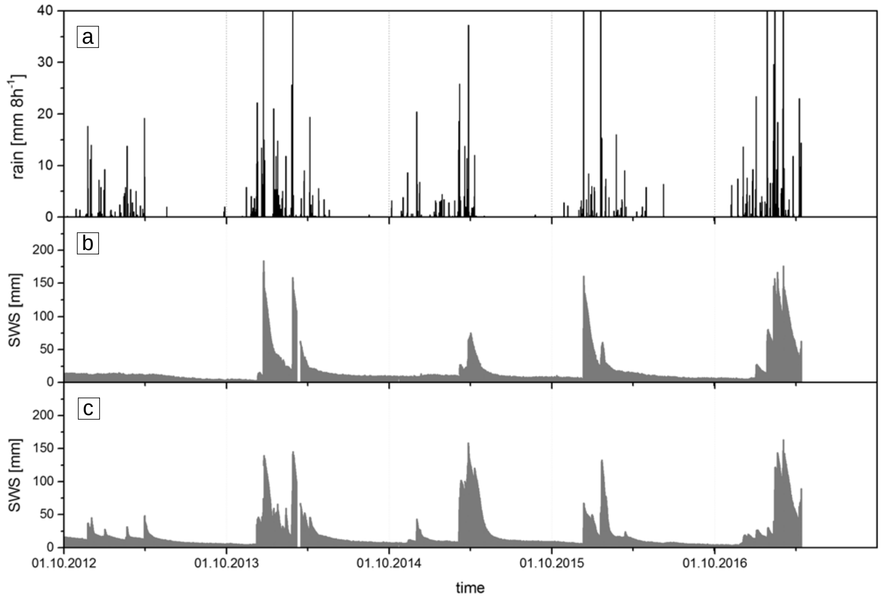

Figure 2: Five years of monitoring of rainfall (a) and soil water storage (SWS) in the below-canopy (b) and intercanopy (c) profiles at plot EL.

was measured with granular matrix sensors (type Watermark 200SS, Irrometer Company Inc., USA) of 22 mm diameter and 83 mm length. The sensors consist of stainless steel electrodes embedded in a defined and consistent internal granular matrix material. The four granular matrix sensors were installed at the same depths as the TDR sensors and connected to a Watermark 900M monitor logger. The logging interval was set to 2 h. The SWP output from the Watermark loggers has been calculated for a predefined soil temperature. We corrected the SWP for the actual soil temperature according to Shock et al. (1998), using the soil temperature measured by the TDR sensors. Significant relationships (field water retention curves) found between measured SWC and SWP were then used to calculate SWP from SWC in periods of missing data. To make inferences on the probability of groundwater recharge, we quantified the number of days per year when deep percolation (i.e., drainage deeper than the deepest sensor at 80 cm) was physically possible (i.e., at SWP ≤ pF 2.5).

Rainfall at each plot was monitored with a tipping bucket (0.2 mm resolution, 15 min logging frequency) in the intercanopy space. Additionally, a SASSCAL climate station has been located on the farm and providing data since November 2010 (www.sasscalweathernet.org; Muche et al., 2018).

At plots EL and ES we monitored soil water dynamics and rainfall for 9 years, from October 2007 to October 2016, and at EG for 5.5 years starting in April 2011, but with roughly 1 year of missing data.

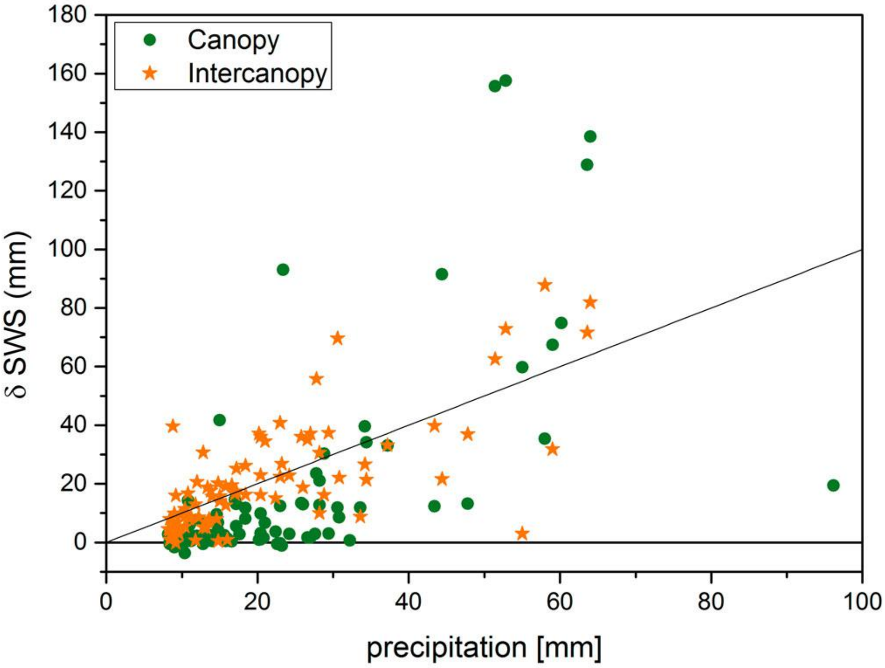

Figure 3: Increase in soil water storage (δ SWS) following rain events (> 8 mm 8h-1) for plot EL (line = 1:1 relation).

Results

The study period was characterized by high inter-annual variability of rainfall. For the 9 years (defined as starting on October 1 and ending on September 30), the mean annual rainfall was 444 mm, varying between 186 mm (2012–2013) and 746 mm (2010–2011). Within the rainy season, the rainfall distribution also varied. Rainfall occurred predominantly between November 20 and April 30, with the long-term maximum monthly rainfall occurring in February.

In relation to the rainfall patterns, highly dynamic water storage in the soils was observed (Fig. 2), controlled by infiltration during stronger precipitation events and the water uptake of plants during the growing season.

Rainwater infiltration

First, we analysed how bushes and trees affect the infiltration of rainwater. To do this we related the rain-induced increase in soil water storage (δ SWS, mm) to the amount of precipitation of all rain events with more than 8 mm precipitation within 8 hours. For smaller rain events, we found no change in soil moisture at all plots and events.

For EL, where the below-canopy profile is located under a large *A. mellifera* patch (see Fig. 1), the relationships between precipitation and δ SWS are shown in Fig. 3. At this plot, we observed that in the intercanopy area:

- rain amounts < 16 mm may not increase soil water content at the first measuring depth (20 cm) and therefore there is also no increase in δ SWS, especially if the soil is initially dry;
- with increasing rain amounts, δ SWS also increases; and
- for some rain events, the increase in soil moisture exceeds the amount of rainfall.

Rain water infiltration below the canopy showed different interactions:

- Even more rain is needed to moisten the soil down to the first sensor (20 cm depth).
- Especially if the soil is initially dry, there is the possibility of a very large increase in soil moisture as a result of rainfall. Here we have registered eight events where δ SWS exceeded the rain amount by a factor of ≥ 1.2 and absolutely by more than 5 mm. As can be seen in Figure 3, the increase in SWS exceeds the rainfall sometimes by a factor of up to nearly four. Of the three most intense rainfalls at this station, two led to the highest observed δ SWS, whereas one event with the highest rainfall amount (2/3/2009, rainfall of 96.2 mm) resulted in a δ SWS of just 19.4 mm.

Although very high infiltration rates have been registered for the below-canopy profile at some events, the sum of all rain events (Tab. 1) shows that the total change in SWS for this profile is 70% of the respective rainfall total, whereas for the intercanopy profile the respective proportion is 100%. For the below-canopy profile, rains with low intensity (< 32 mm) frequently did not lead to increased soil water contents, whereas for the intercanopy profile changes in SWS occurred irrespective of rainfall intensity.

For ES the number of registered rain events was lower (Tab. 2) and the difference between below-canopy (71% infiltration of precipitation) and intercanopy (87%) was not as pronounced as at EL.

For plot EG, the number of analysed rain events was lower than for the other plots. Here, the summed rainwater in-

Table 1: Rainwater infiltration at plot EL – Summary of all events (BC = Below-Canopy; IC = Intercanopy).

Rainfall Class	Number of Rain Events Analysed		Mean Rainfall		Total Rainfall		Total δ SWS		Mean δ SWS		Percentage δ SWS of Rainfall	
	BC	IC	BC	IC	BC	IC	BC	IC	BC	IC	BC	IC
mm			mm	mm	mm	mm	mm	mm	mm	mm	%	%
8–16	52	41	11.7	11.6	605.9	474.8	146.7	419.8	2.8	10.2	24.2	88.4
16–24	18	15	20.2	19.9	363.0	298.8	176.7	373.0	9.8	24.9	48.7	124.8
24–32	13	12	27.8	27.8	361.0	333.4	146.7	391.7	11.3	32.6	40.6	117.5
32–40	5	4	34.3	34.9	171.6	139.4	119.4	90.0	23.9	22.5	69.6	64.6
40–48	3	3	45.2	45.2	135.6	135.6	117.0	98.3	39.0	32.8	86.3	72.5
48–56	3	3	53.1	53.1	159.2	159.2	373.1	138.5	124.4	46.2	234.4	87.0
56–64	5	4	61.0	61.2	304.8	244.6	444.9	273.1	89.0	68.3	146.0	111.7
> 64	1	0	96.2		96.2		19.4		19.4		20.2	
all	100	82			2,197.3	1,785.8	1,543.9	1,784.4			**70.3**	**99.9**

Table 2: Rainwater infiltration at plot ES – Summary of all events (BC = Below-Canopy; IC = Intercanopy).

Rainfall Class	Number of Rain Events Analysed		Mean Rainfall		Total Rainfall		Total δ SWS		Mean δ SWS		Percentage δ SWS of Rainfall	
	BC	IC	BC	IC	BC	IC	BC	IC	BC	IC	BC	IC
mm			mm	mm	mm	mm	mm	mm	mm	mm	%	%
8–16	18	24	11.6	11.6	208.7	278.2	66.2	161.1	3.7	6.7	31.7	57.9
16–24	13	15	19.6	19.5	254.4	291.8	176.9	254.2	13.6	16.9	69.5	87.1
24–32	10	10	26.4	26.4	264.0	264.0	216.2	287.1	21.6	28.7	81.9	108.8
32–40	8	9	36.1	36.4	288.4	327.4	231.7	297.6	29.0	33.1	80.3	90.9
40–48	2	2	43.2	43.2	86.4	86.4	57.1	79.4	28.6	39.7	66.1	91.9
48–56	3	3	52.3	52.3	156.8	156.8	137.2	166.1	45.7	55.4	87.5	105.9
56–64	0	0										
> 64	2	2	88.9	88.9	177.8	177.8	134.5	131.8	67.3	65.9	75.6	74.1
all	56	65			1,436.5	1,582.4	1,019.8	1,377.2			**71.0**	**87.0**

Table 3: Rainwater infiltration at plot EG – Summary of all events (1 = Grass 1; 2 = Grass 2); Frequency of moist subsoil water potentials (SWP).

Rainfall Class	Number of Rain Events Analysed	Mean Rainfall	Total Rainfall	Total δ SWS		Mean δ SWS		Percentage δ SWS of Rainfall	
	1 & 2	1 & 2	1 & 2	1	2	1	2	1	2
mm		mm	mm	mm	mm	mm	mm	%	%
8–16	17	11.5	195.4	324.4	104.8	19.1	6.2	166.0	53.6
16–24	11	19.5	214.2	934.5	198.1	85.0	18.0	436.3	92.5
24–32	3	28.4	85.2	188.1	115.7	62.7	38.6	220.8	135.8
32–40	2	38.2	76.4	151.3	61.1	75.7	30.6	198.0	80.0
40–48	1	47.8	47.8	48.7	35.4	48.7	35.4	101.9	74.1
48–56	1	51.8	51.8	62.7	50.0	62.7	50.0	121.0	96.5
56–64	0								
> 64	0								
all	35		670.8	1,709.7	565.1			**254.9**	**84.2**

filtration differed substantially between the two neighboring profiles (Tab. 3). Whereas for profile 2 the proportion of infiltrated rain was similar to that of the intercanopy profiles of the other plots (84%), for profile 1 the infiltration exceeded the rainfall by a factor of 2.5.

Soil water losses through evapotranspiration

Because of pronounced wet and dry seasons in Namibian savannas and resultant adaptations in vegetation, plant growth is generally low to very low from June to October and high from December to April. This activity pattern is reflected in the soil water storage (Fig. 4). The example of the below-canopy patch of plot EL indicates that daily water losses (δ SWS) by evapotranspiration (ET) may increase in November with the greening vegetation; may further increase until mid-March, when peak rates of ET of 6.8 mm d^{-1} have been measured; and strongly decreases until the end of May.

In general, the daily losses of soil water through root water uptake are controlled by climatic conditions (temperature, vapour pressure deficit (VPD), and wind) and soil moisture availability. Thus, even in the rainy season, low ET has been observed on days with low VPD. During the dry season (from June to October), a much lower ET was observed.

With the reduction of the soil moisture potential, a substantial decline in actual ET has been found for the below-canopy patch of plot EL (Fig. 5). Here, daily δ SWSs of more than 5 mm are restricted to moist soils (SWP < pF 2.4), and at SWP > pF 3, daily δ SWSs are smaller than 1.5 mm.

Compared to the below-canopy profile, in the intercanopy area the reliability of high daily ET on days with moist soils (pF < 2.5) is much less (Fig. 6).

To compare the δ SWS for all profiles, the measured SWPs were put in classes of 0.2 pF width and the distribution of corresponding δ SWS analysed. The daily median δ SWSs for each SWP class (Fig. 7) indicate that under moist conditions (pF < 2.5) the daily soil moisture losses are larger for both below-canopy profiles compared to the respective intercanopy profiles.

Deep percolation

Deep percolation is the outflow of water through the lower boundary of the soil, here defined as a 1 m depth below soil surface. Although no direct measurement of deep percolation is possible, the existing data allow some inferences to be made on this component. The deepest sensors monitoring SWP were installed a depth of 80 cm. The SWP is known to be directly related to the hydraulic conductivity of the soil because as SWP increased, larger pores of the soil become water filled and thus the flow resistance decreases. If SWP gradients exist, water flow is directed from places with high SWP to those with low SWP, typically from moist to dry soil horizons (following matrix potentials) or from topsoil to subsoil (following gravitational potentials). The flow rate (Q) is described by Darcy's law, which says that Q is proportional to the hydraulic conductivity K(ψ) and the potential gradient δ SWP/L.

Table 4: Frequency of moist subsoil water potentials (SWP)

Plot	Profile	Time Period	*n*	Number of Days with SWP ≤ 2.5 pF	Number of Days with SWP ≤ 1.8 pF	Number of Days with SWP ≤ 1.5 pF
ES	IC	10/2007 – 10/2016	3106	594	94	43
	BC		3136	342	23	0
EL	IC		3100	521	150	102
	BC		3121	207	27	8
ES	IC	4/2011 – 10/2016	2005	355	54	36
	BC		2032	149	13	0
EL	IC		2019	317	72	53
	BC		2032	59	0	0
EG	Grass1		2036	416	5	0
	Grass2		2035	259	5	3

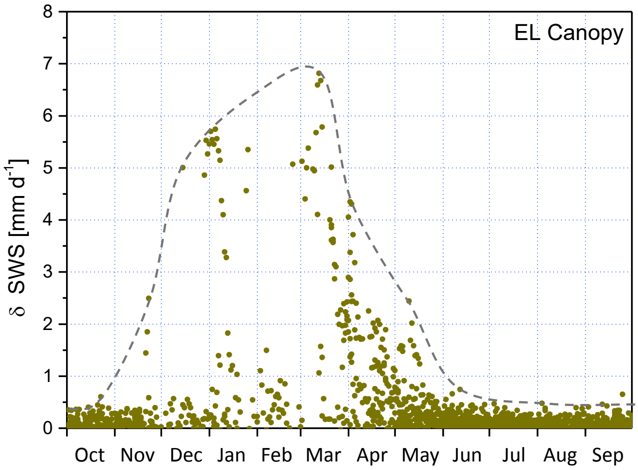

Figure 4: Daily losses of soil water storage (δ SWS) within the season (EL below-canopy). The dotted line indicates the evapotranspiration potential of the vegetation.

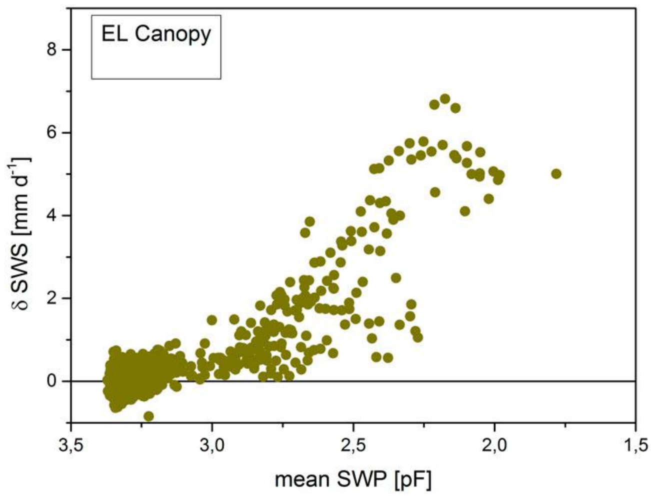

Figure 5: Daily losses of soil water storage (δ SWS) in relation to soil water potential (EL below-canopy).

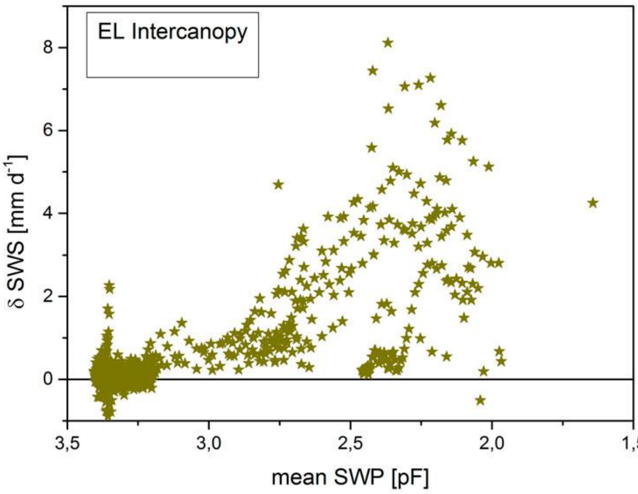

Figure 6: Daily losses of soil water storage (δ SWS) in relation to soil water potential (EL intercanopy).

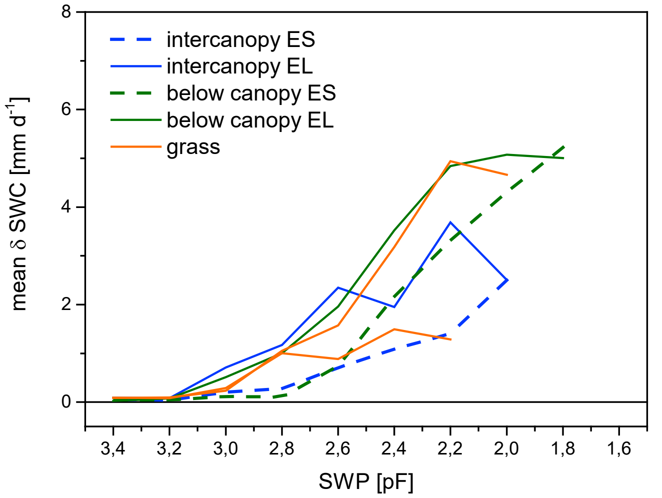

Figure 7: Median of the classified relationship between δ SWS and SWP for all profiles.

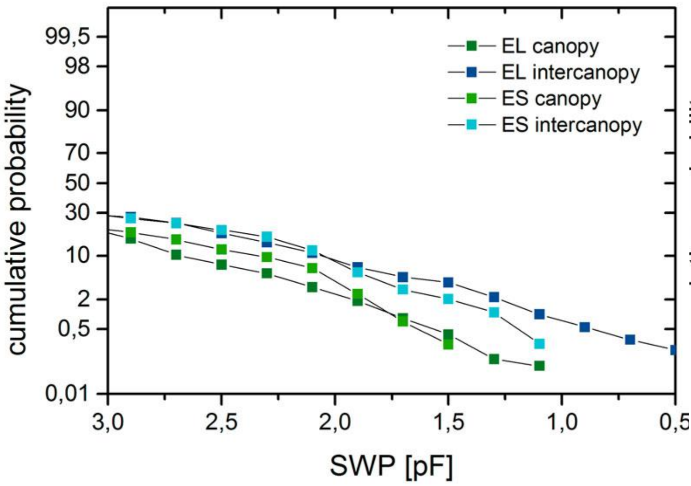

Figure 8: Cumulative probability of SWP at 80 cm depth for the phase Oct. 2007–Oct. 2016. The large proportion of dry subsoils (SWP > pF 3, p > 70 %) is not shown.

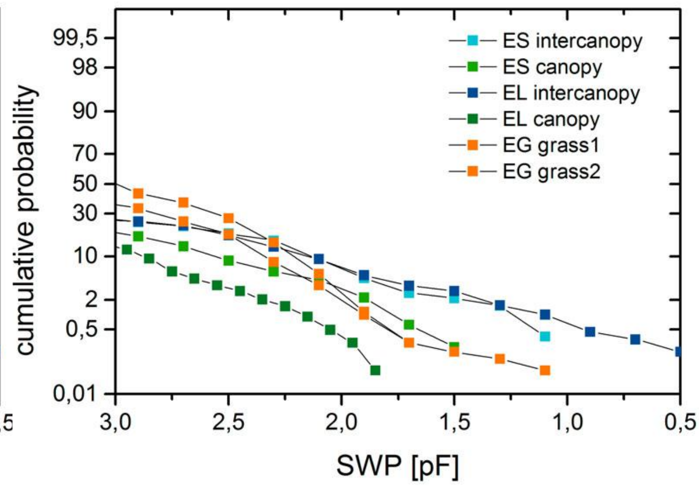

Figure 9: Cumulative probability of SWP in 80 cm depth for the phase April 2011–Oct. 2016. The large proportion of dry subsoils (SWP > pF 3, p > 70 %) is not shown.

Table 5: Weighted probabilities of deep percolation

Plot and Profile	Time Period 10/2007–10/2016	Time Period 4/2011–10/2016
ES – Intercanopy	47.6	40.7
ES – Below-canopy	15.9	15.0
EL – Intercanopy	55.7	42.7
EL – Below-canopy	14.5	2.1
EG – Grass1		13.8
EG – Grass2		10.1

Cumulative probabilities of the SWP for the subsoil (80 cm depth) show that for both bush-encroached plots (EL and ES), the probability of high SWP is significantly larger for the intercanopy profiles than for the below-canopy profiles (Tab. 4, Fig. 8). For example, for the SWP class of 2.0–2.2 pF (centre 2.1 pF), the cumulative probability (p) for the intercanopy profiles is $p = 11.7$ at ES and $p = 11.0$ at EL, whereas for the below-canopy profiles the probabilities are lower: $p = 6.7$ at ES and $p = 3.3$ at EL.

The same type of analysis appears in Figure 9, but restricted to the period of April 2011 to October 2016. This is the period for which simultaneous data from plot EG were available and which consisted of drier seasons. Because of the larger proportion of dry periods, the cumulative probabilities of high SWP are lower compared to the data given in Figure 8. For example, for the SWP class of 2.0–2.2 pF (centre 2.1 pF), the cumulative probabilities for the intercanopy profiles are $p = 9.1$ at ES and $p = 9.2$ at EL, whereas for the below-canopy profiles they are $p = 4.5$ at ES and $p = 0.7$ at EL. Additionally, both profiles on plot EG with grass vegetation show a cumulative probability similar to that of the ES below-canopy profile, with $p = 5.6$ and $p = 3.6$ for pF = 2.1.

To quantify the potential deep percolation, the probabilities of SWP were multiplied by the unsaturated hydraulic conductivity ($K(\psi)$) of the SWP class centre and subsequently summed per probability class (Tab. 5). $K(\psi)$ was derived from laboratory analysis, but restricted to a maximum percolation rate of 10 mm d^{-1}. Because of the increasing $K(\psi)$ with increasing SWP, the difference between the below-canopy profiles and the intercanopy profiles becomes larger. For the total time period (Oct. 2007–Oct. 2016), the probability of deep percolation in the intercanopy space is 3.17 (ES) or 3.84 (EL) times higher than in the below-canopy space. Within the shorter period (April 2011 to Oct. 2016), the probability of deep percolation of both grass profiles at EG is in the range of the ES below-canopy profile and lower than both intercanopy profiles.

Discussion

Reliability of the measured data

In general, the measurement of soil water state properties may be compromised by soil disturbance associated with sensor installation, by systematic errors of the sensors and logging systems, and by particular soil features (e.g., presence of stones) at the measured position. All influences may result in data which are biased and difficult to interpret. We controlled the reliability of the three types of independent automatic devices (rain gauges, soil water content sensors, soil water potential sensors) by assessing (1) relationships between data sets, (2) plausibility checks, and (3) consistency with laboratory data. For the rain gauges, the inter-station comparisons helped to define periods in which individual rain gauges were most likely deficient. For the measurements of SWP, a robust and simple system was applied that was not influenced by the surrounding soil matrix and that showed no signs of long-term trends. SWC was measured with TDR sensors of 100 mm rod length, which were individually calibrated with dry air and pure water before installation. The reliability of SWP and SWC data sets was checked by visual inspection of the “field soil water retention curves” to see whether the shape of the curves reflected typical soil water dynamics. For many soil depth intervals we found a significant relationship between the two independent field measurements, which implied that both types of sensors were able to react to changes in soil moisture simultaneously and in an expected way. From all checks we concluded that, in general, reliable data had been obtained from both types of soil water sensors. We therefore assumed that the unexpected increase in SWC observed at different profiles during some rain events reflected natural processes and was not caused by a malfunction of the sensors. Nevertheless, the necessity of opening a pit to install the sensors and the impossibility of refilling the pit in a way that mimicked the original condition may have caused changes in the soil water dynamics at the pit position. Most likely, this effect was stronger when soil water flows were influenced by preferential flows in macropores and when soil moisture was high.

Impact of bush encroachment on the infiltration process

At all plots, rain events were observed during which increases in SWS (δ SWS) were greater than the measured rainfall amounts (P). One explanation for this phenomenon could be the influence of stemflow from *A. mellifera*. The funnel-shaped and smooth-barked stems of *A. mellifera* are expected to be able to collect rainwater and transfer it to the base of the stem (stemflow; for shrubs of other arid environments, see Martinez-Meza & Whitford, 1996). However, this phenomenon cannot solely explain our observation, since we observed the largest differences at EG, where trees were absent. A more likely explanation is that positive differences between δ SWS and P were related to soil surface run-on to the measuring position at moments of high rainfall. All three positions are almost flat

Rangelands

with a topsoil composed of sandy loam (ES, EL) or sandy clay loam (EG). The aggregate stability of the topsoil is low, and under splashing rainfall, the structure tends to break down and form a low-permeable topsoil crust. Ponding water on the soil surface with at least short-distance flows has frequently been observed at the investigation site.

Additionally, inhomogeneous infiltration patterns may be enhanced by preferential flow systems within the soils as produced by shrinkage or the activity of burrowing soil organisms. We observed that immediately after strong rain events, the water content increased rapidly even at a 60 cm depth and concluded that preferential flow phenomena are common in these dense soils. Because of the higher clay content of the soils at plot EG, these flow systems are likely to be more stable there than at the other plots.

Our results show that if the topsoil was dry, it was likely that the sensors in the uppermost depth (20 cm depth) did not show an increase in SWC or SWP, as the rainwater did not reach the 20 cm depth. The precipitation range that registered no response was smallest in the cleared plot (EG) (0–13.5 mm), intermediate in the intercanopy profiles (EL and ES) and the profile below an *A. mellifera* bush (ES) (0–18 mm), and largest under the canopy of a large *A. mellifera* at EL (0–32 mm). This increase in precipitation range with increasing canopy coverage can be attributed to two processes: first, the interception by leaves and branches and subsequent evaporation, and second, the storage of the rainfall proportion reaching the soil surface within the upper soil layer. Here, based on the analysis of the pore distribution, it appears that about 15 to 20 mm of water may be stored in the upper 10 cm of soil.

A summary of the δ SWS of all rain events (> 8 mm 8 h^{-1}) shows a clear reduction of infiltration below larger and smaller canopies (Fig. 10). Under tree canopies, the nine-year cumulative deficit between rainfall and infiltration is 29–33 %. Considering that this proportion is reduced by run-on in the below-canopy area, the deficit may be even larger (e.g., 29–55%) if only the minimum amount of run-on is taken into ac-

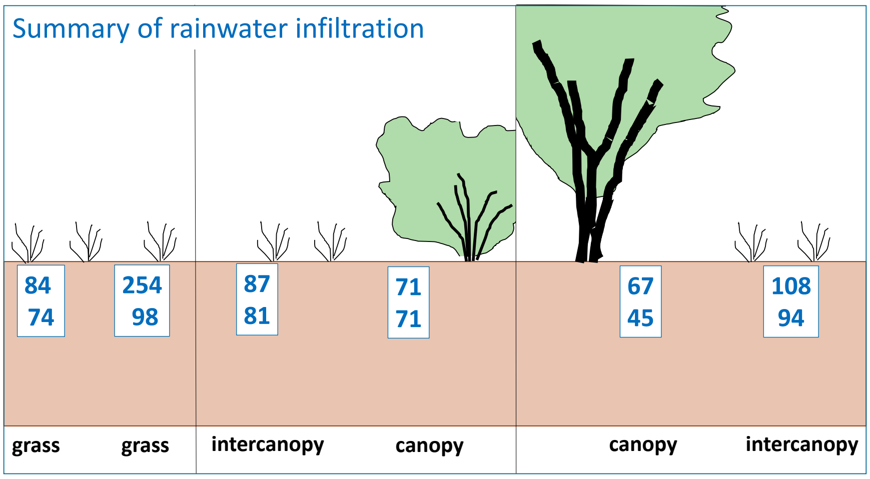

Figure 10: Summary of the proportion of rainfall infiltration (%): Upper value: all events uncorrected. Lower value: all events corrected with lowest estimate of run-on.

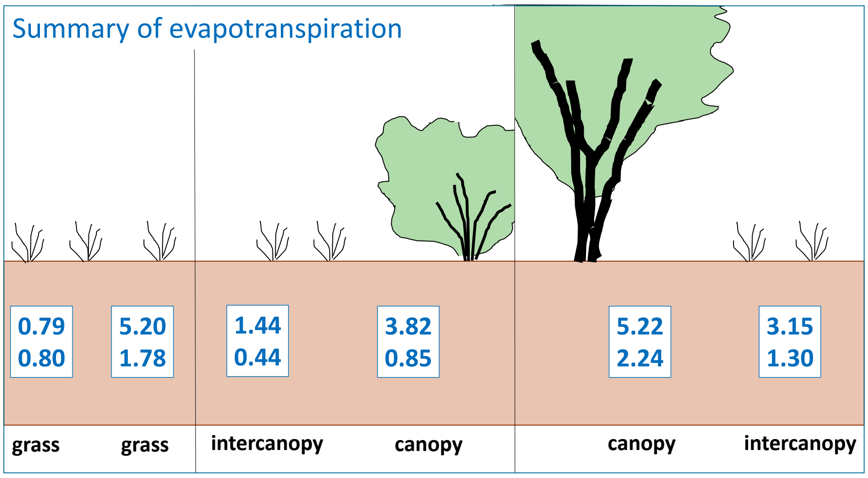

Figure 11: Summary of estimated daily water losses by evapotranspiration (ET, mm d-1): Upper value: median ET for moist soils (pF 1.9 < SWP < pF 2.3); Lower value: median ET for intermediate soils (pF 2.9 < SWP < pF 2.3).

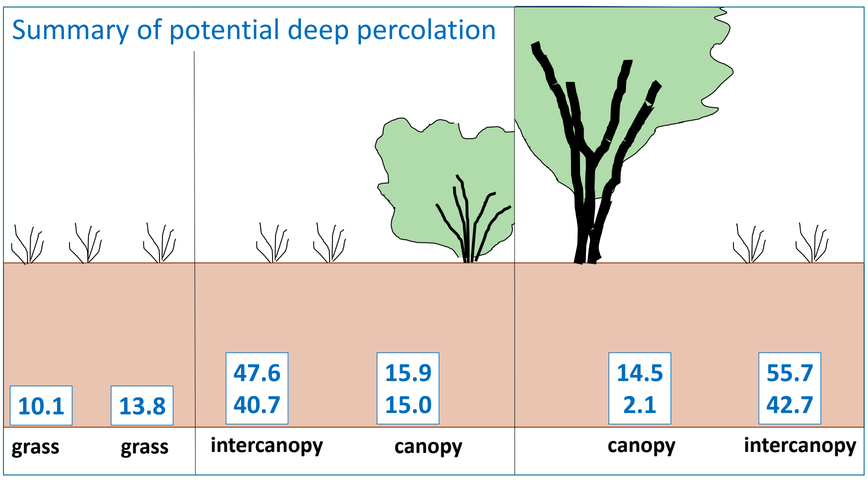

Figure 12: Summary of potential deep percolation. Upper row: weighed percentage for the period Oct. 2007–Oct. 2016; Lower row: weighted percentage for the period April 2011–Oct. 2016.

count. In a two-year study, Belsky et al. (1989) found a reduction of rainfall below canopies of *A. tortilis* and *A. digitata* compared to open grassland on the same order of magnitude (0–50 %). The difference between the rainfall and infiltration amounts may result from interception, which depends on rainfall intensity and duration and may vary in stands of savanna trees between 1 and 5 mm per rain event (De Villiers, 1982). According to Scholes & Walker (1993), however, mean interception is only 2 mm per rain event, an amount that still leaves us with a deficit of about 20% of the mean rainfall. Additional processes that might contribute to the deficit between rainfall and the sum of infiltration and interception are (1) the water storage above the upper soil moisture sensor and (2) stemflow that is not reaching the measurement position. Moreover, run-off could have resulted in reduced infiltration, but this is not very likely given the higher proportion of macropores in the topsoil below trees and the reduction of the raindrop energy through the canopy, both factors that reduce the possibility of run-off from under the canopy to nearby positions.

Impact of bush encroachment on the consumption of soil moisture

We analysed the losses in soil water content (δ SWS) in relation to soil water potential (SWP). These losses are the sum of evaporation and transpiration and possibly deep percolation; as losses were calculated for the whole soil profile up to the depth of 1 m, however, the proportion of evaporation is low and losses might be dominated by transpiration of the plant cover.

In general, there is a strong reduction in evapotranspiration with decreasing soil water availability; at pF 3.0 for all profiles, even the 90th percentile of daily δ SWS is ≤ 1 mm d^{-1} water loss by ET. In the case of moist soils (SWP < pF 2.3), each of the studied vegetation types was able to transpire large amounts of water per day. The 90th percentile for all three types of vegetation cover (trees, intercanopy dwarf shrubs and herbs, grasses) has a maximum of 6.1 to 6.7 mm d^{-1}. However, this potential is most likely realized only in the case of well-developed vegetation stages. Sapflow measurements of *Acacia nigrescens* trees in the Kruger National Park resulted in peak transpiration of 80 mm/month and about 210 mm/year related to the canopy area basis (Dye et al., 2008), which is less than the cumulative water losses that we observe. However, the δ SWS, which is the basis of our calculation, comprises not only tree transpiration but also the transpiration of the below-canopy herbs and soil evaporation. For the intercanopy and one grass profile, the variation in daily water consumption at identical soil moisture conditions is large. In contrast, for the below-canopy profile under a large *A. mellifera* tree at plot EL, the daily water uptake is strongly correlated to the SWP (Fig. 5).

Comparing evaporation under tree canopies with intercanopy patches of ES and EL clearly shows that soil moisture below canopies is consumed at higher daily rates than in the respective intercanopies (Fig. 11). The ratio $ET_{below\text{-}canopy}/ET_{intercanopy}$ varies between 1.7 and 2.7. The absolute values of calculated ET at one of the two grass profiles, however, are the same as the calculated daily ET for the large *A. mellifera* at EL.

The difference in daily ET between below-canopy and intercanopy patches is complicated, however, by the variation in available soil moisture. As rainwater infiltration is less below canopies than in the intercanopy, clear differences in ET are less evident. In addition, the available water below canopies is transpired faster than in the intercanopy area, resulting in greater SWS for the intercanopy profiles, particularly at the end of the rainy season. Focusing on the differences in soil chemical and physical properties below *Acacia raddiana* trees compared to outside grass areas, De Boever et al. (2016) concluded that the trees can positively affect the below-canopy water availability. In our study, the positive physical topsoil properties could not compensate for the reduced amount of infiltrating water.

Impact of bush encroachment on potential deep percolation

As a consequence of differences in infiltration and evapotranspiration amounts between below-canopy and intercanopy patches, the frequency of soil water availability in the subsoil and thus potential deep percolation are altered by presence of trees (Fig. 12). Over the nine-year measurement period of this study, both intercanopy profiles exhibited potential for deep percolation on the order of 3.0 (plot ES) to 3.8 (plot EL) times more than the respective below-canopy profiles. This was the result of both higher infiltration and less evapotranspiration at the intercanopy profiles. The grass plot, which could be compared to the other plots only from 2011 onwards, showed potential for deep percolation that is in the range of the below-canopy profile ES, but larger than that of the below-canopy profile EL. The general difference in the soil-water dynamics between the grass plot and the other two bush-encroached plots is suspected to result from the higher clay content and the thicker soil cover above the bedrock at the grass plot. In general, the lower groundwater recharge below trees is in line with findings from other water-restricted ecosystems (Lubczinsky, 2009), but the magnitude of the role of trees was not reported yet. As roots of *A. mellifera* are known to extend beyond the canopy area, it is likely that the effect of trees on potential deep percolation is even larger than calculated here.

At the intercanopy profile EL, soil water potentials approaching saturation (SWP < pF 1.0) were observed on some days. These values indicate a reduced potential for deep percolation at the lower boundary of the soil profile through the underlying saprolite into the granitic bedrock.

Conclusions

On the plot scale we observed (1) an increase in soil moisture larger than precipitation at some rain events, interpreted as water run-on at moments of surface ponding; (2) in total a reduced infiltration of water in the below-canopy area of *A. mellifera* compared to the intercanopy space; and (3) a more constant and thus faster reduction of soil moisture in the below-canopy space because of root water uptake, which resulted in the potential for deep drainage being approximately three times greater in the intercanopy space in comparison with the below-canopy space. These processes on the local scale are the background to understand hydrological processes on the landscape scale.

Although we found clear impacts on potential deep percolation as a result of the presence of tree canopies, the links between observed soil water dynamics and groundwater level changes remain unknown. At present, the data necessary to study this interrelation are not available, and the measuring infrastructure for groundwater monitoring does not yet exist at the study sites. The relocation of water by surface run-off and run-on, the potential water redistribution by hydraulic lift, and the likely influence of soil organisms such as termites are environmental factors that heighten the complexity of the water dynamics in these water-restricted ecosystems and limit the successful application of hydrological models. To solve the open questions regarding the effects of bush encroachment and de-bushing on groundwater recharge, a larger-scale analysis of groundwater dynamics needs to be combined with (a) soil water monitoring as done in this study, (b) analysis of the water consumption patterns of main encroacher species using sap-flow measurements, and (c) monitoring of the vegetation dynamics.

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References

Archer, S.R. (2010) Rangeland conservation and shrub encroachment: New perspectives on an old problem. *Wild rangelands: Conserving wildlife while maintaining livestock in semi-arid ecosystems* (ed. by J.T. du Toit, R. Kock, & J.C. Deutsch), pp. 53–97. Blackwell Scientific Publications, Oxford.

Belsky, A., Amundson, R., Duxbury, J., Riha, S., Ali, A. & Mwonga, S. (1989) The effects of trees on their physical, chemical and biological environments in a semi-arid savanna in Kenya. *Journal of Applied Ecology,* **26**, 1005–1024.

Briggs, J.M., Knapp, A.K., Blair, J.M., Heisler, J.L., Hoch, G.A., Lett, M.S. & McCarrion, J.K. (2005) An ecosystem in transition: causes and consequences of the conversion of mesic grassland to shrubland. *BioScience,* **55**, 243–254.

Christian, C. (2010) *The effect of bush encroachment on groundwater resources in Namibia: A desk top study.* Colin Christian & Associates CC, Windhoek, Namibia.

De Boever, M., Gabriels, D., Ouessar, M. & Cornelis, W. (2016) Influence of *Acacia* trees on near-surface soil hydraulic properties in arid Tunisia. *Land Degradation & Development,* **27**, 1805–1812.

De Klerk, N. (2004) *Bush encroachment in Namibia*. Windhoek, Namibia.

De Villiers, G. Du T. (1982) Predictive models for estimating net rainfall and interception losses in savanna vegetation. *Water SA*, **8**, 208–211.

Dye, P.J., Gush, M.B., Everson, C.S., Jarmain, C., Clulow, A., Mengistu, M., Geldenhuys, C.J., Wise, R., Scholes, R.J., Archibald, S. & Savage, M.J. (2008) Water use in relation to biomass of indigenous tree species in woodland, forest and/or plantation conditions. WRC report no. TT361/08. Water Research Commission, Pretoria, South Africa.

Eldridge, D.J., Bowker, M.A., Maestre, F.T., Roger, E., Reynolds, J.F. & Whitford, W.G. (2011) Impacts of shrub encroachment on ecosystem structure and functioning: Towards a global synthesis. *Ecology Letters,* **14**, 709–722.

Kinzelbach, W., Aeschbach, W., Alberich, C., Goni, I., Beyerle, U., Brunner, P., Chiang, W., Rueedi, J. & Zoellmann, K. (2002) A survey of methods for groundwater recharge in arid and semi-arid regions. Early warning and assessment report series, UNEP/DEWA/RS 2(2).

Lubczynski, M.W. (2009) The hydrogeological role of trees in water-limited environments. *Hydrogeology Journal,* **17**, 247–259.

Martinez-Meza, E., & Whitford, W.G. (1996) Stemflow, throughfall and channelization of stemflow by roots in three Chihuahuan desert shrubs. *Journal of Arid Environments*, **32**, 271–287.

Mendelsohn, J., Jarvis, A., Roberts, C. & Robertson, T. (2009) *Atlas of Namibia: A portrait of the land and its people.* David Philip Publishers, Cape Town, South Africa.

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: present state, challenges, and achievements of the regional climatic measuring network and database. This volume.

O'Connor, T.G., Puttick, J.R. & Hoffman, M.T. (2014) Bush encroachment in southern Africa: Changes and causes. *African Journal of Range & Forage Science*, **31**, 67–88.

Petersen, A. (2008) Pedodiversity of southern African drylands. PhD thesis, University of Hamburg, Hamburg.

Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gaye, C.B., Edmunds, W.M. & Simmers, I. (2006) Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes*, **20**, 3335–3370.

Scholes, R.J. & Archer, S.R. (1997) Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics*, **28**, 517–544.

Scholes, R.J. & Walker, B.H. (1993) An African savanna: Synthesis of the Nylsvley study. Cambridge University Press, Cambridge.

Shock, C.C., Barnum, J.M. & Seddigh, M. (1998) Calibration of Watermark soil moisture sensors for irrigation management. *Proceedings of the International Irrigation Show*, 139–146.

Van Auken, O. W. (2000) Shrub invasions of North American semiarid grasslands. *Annual Review of Ecology and Systematics*, **31**, 197-215.

Ward, D. (2005) Do we understand the causes of bush encroachment in African savannas? *African Journal of Range and Forage Science*, **22**, 101–105.

References [CrossRef]

Archer, S.R. (2010) Rangeland conservation and shrub encroachment: New perspectives on an old problem. *Wild rangelands: Conserving wildlife while maintaining livestock in semi-arid ecosystems* (ed. by J.T. du Toit, R. Kock, & J.C. Deutsch), pp. 53–97. Blackwell Scientific Publications, Oxford.

Belsky, A., Amundson, R., Duxbury, J., Riha, S., Ali, A. & Mwonga, S. (1989) The effects of trees on their physical, chemical and biological environments in a semi-arid savanna in Kenya. *Journal of Applied Ecology*, **26**, 1005–1024. CrossRef

Briggs, J.M., Knapp, A.K., Blair, J.M., Heisler, J.L., Hoch, G.A., Lett, M.S. & McCarrion, J.K. (2005) An ecosystem in transition: causes and consequences of the conversion of mesic grassland to shrubland. *BioScience*, **55**, 243–254. CrossRef

Christian, C. (2010) *The effect of bush encroachment on groundwater resources in Namibia: A desk top study.* Colin Christian & Associates CC, Windhoek, Namibia.

De Boever, M., Gabriels, D., Ouessar, M. & Cornelis, W. (2016) Influence of *Acacia* trees on near-surface soil hydraulic properties in arid Tunisia. *Land Degradation & Development*, **27**, 1805–1812. CrossRef

De Klerk, N. (2004) *Bush encroachment in Namibia*. Windhoek, Namibia.

De Villiers, G. Du T. (1982) Predictive models for estimating net rainfall and interception losses in savanna vegetation. *Water SA*, **8**, 208–211.

Dye, P.J., Gush, M.B., Everson, C.S., Jarmain, C., Clulow, A., Mengistu, M., Geldenhuys, C.J., Wise, R., Scholes, R.J., Archibald, S. & Savage, M.J. (2008) Water use in relation to biomass of indigenous tree species in woodland, forest and/or plantation conditions. WRC report no. TT361/08. Water Research Commission, Pretoria, South Africa.

Eldridge, D.J., Bowker, M.A., Maestre, F.T., Roger, E., Reynolds, J.F. & Whitford, W.G. (2011) Impacts of shrub encroachment on ecosystem structure and functioning: Towards a global synthesis. *Ecology Letters*, **14**, 709–722. CrossRef

Kinzelbach, W., Aeschbach, W., Alberich, C., Goni, I., Beyerle, U., Brunner, P., Chiang, W., Rueedi, J. & Zoellmann, K. (2002) A survey of methods for groundwater recharge in arid and semi-arid regions. Early warning and assessment report series, UNEP/DEWA/RS 2(2).

Lubczynski, M.W. (2009) The hydrogeological role of trees in water-limited environments. *Hydrogeology Journal*, **17**, 247–259. CrossRef

Martinez-Meza, E., & Whitford, W.G. (1996) Stemflow, throughfall and channelization of stemflow by roots in three Chihuahuan desert shrubs. *Journal of Arid Environments*, **32**, 271–287. CrossRef

Mendelsohn, J., Jarvis, A., Roberts, C. & Robertson, T. (2009) *Atlas of Namibia: A portrait of the land and its people.* David Philip Publishers, Cape Town, South Africa.

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: present state, challenges and achievements of the regional climatic measuring network and database. This volume. CrossRef

O'Connor, T.G., Puttick, J.R. & Hoffman, M.T. (2014) Bush encroachment in southern Africa: Changes and causes. *African Journal of Range & Forage Science*, **31**, 67–88. CrossRef

Petersen, A. (2008) Pedodiversity of southern African drylands. PhD thesis, University of Hamburg, Hamburg.

Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gaye, C.B., Edmunds, W.M. & Simmers, I. (2006) Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes*, **20**, 3335–3370. CrossRef

Scholes, R.J. & Archer, S.R. (1997) Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics*, **28**, 517–544. CrossRef

Scholes, R.J. & Walker, B.H. (1993) An African savanna: Synthesis of the Nylsvley study. Cambridge University Press, Cambridge. CrossRef

Shock, C.C., Barnum, J.M. & Seddigh, M. (1998) Calibration of Watermark soil moisture sensors for irrigation management. *Proceedings of the International Irrigation Show*, 139–146.

Van Auken, O. W. (2000) Shrub invasions of North American semiarid grasslands. *Annual Review of Ecology and Systematics*, **31**, 197-215. CrossRef

Ward, D. (2005) Do we understand the causes of bush encroachment in African savannas? *African Journal of Range and Forage Science*, **22**, 101–105. CrossRef

Forage quality and availability for large herbivores in southern African rangelands

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Rangelands

Abstract: In light of the growing human population, the pressure on herbivores (livestock and wild herbivores) will be accelerated, resulting in a need for effective land management. To achieve this, information and knowledge about the availability and quality of food resources of large herbivores and possible changes in those resources are a prerequisite. In this chapter, we will summarize different projects conducted regarding food availability and quality within SASSCAL. We will give an example of the use of remote sensing as an effective tool for measuring food availability and quality on a large scale. Here, we visualize changes in leaf nitrogen concentration and annual grass biomass. In two other projects, we studied different aspects of plant response. In a fence-line study, we investigated the influence of overgrazing on the plant quality of grasses. Though we detected positive impacts on plant quality, but due to high grazing pressure, the reduction in biomass resulted in an overall decline in the quality of the overgrazed site. In the other project, we tested the plant response of bush encroacher species to damage by herbivores. In contrast to the grasses of the fence-line study, in the shrub species we observed a tendency for reduced protein concentration. The reduction varied among the different plant species, but it did not have consequences on subsequent consumers (Boer goats). In our last project we focused on the impact of increased temperature and reduced humidity on the plant quality of five grass species. Here, we found a species-specific response. We conclude the article with a synthesis and an outline of possible management implications derived from the different studies.

Resumo: Devido ao crescimento da população humana, a pressão nos herbívoros (gado e herbívoros selvagens) irá acelerar, resultando na necessidade da gestão efectiva da paisagem. Para atingir este objectivo, é necessário informação e conhecimento sobre a disponibilidade e qualidade dos recursos alimentares de grandes herbívoros, e possíveis alterações. Neste capítulo, resumimos diferentes projectos realizados dentro do tópico da disponibilidade e qualidade de alimento no contexto do SASSCAL. Daremos um exemplo de detecção remota como uma ferramenta útil para a medição da disponibilidade e qualidade do alimento em grande escala. Aqui, visualizamos alterações das concentrações de azoto foliar e da biomassa anual das gramíneas. Em dois outros projectos, estudámos diferentes aspectos da resposta de plantas. Num estudo de cercas, investigámos a influência do pastoreio excessivo na qualidade das ervas. Por um lado, detectámos impactos positivos na qualidade das plantas. Porém, por outro lado, a reducção da biomassa resultou num declínio geral da qualidade do local sobrepastoreado. No outro projecto, testámos a resposta de espécies invasoras lenhosas aos danos provocados por herbívoros. Ao contrário das gramíneas do estudo de cercas, observámos uma tendência para a redução da concentração de proteína nas espécies arbustivas. A redução variou entre as diferentes espécies de plantas, mas não teve consequências nos consumidores subsequentes (cabras boer). No nosso último projecto, focámo-nos no impacto do aumento da temperatura e redução da humidade na qualidade de cinco espécies de gramíneas. Aqui, descobrimos uma resposta específica da espécie. Concluimos o artigo com uma síntese e descrevemos possíveis implicações de gestão derivadas dos diferentes estudos.

General introduction

The extraordinary impact of large herbivores on terrestrial ecosystems has already been pointed out in the overview chapter on rangelands (Ramoelo et al., 2018). A growing human population will lead to more intense use of landscapes, including increased demands for meat satisfied by either a growing number of livestock or higher hunting rates for wild herbivores (so-called bush meat). As a result of different factors, however, land degradation has become a severe threat, especially in areas that depend on livestock and game farming (Lehmann et al., 2009). An accelerated habitat loss for wild animals and pasture loss for livestock is projected for vast areas of southern Africa (Harris et al., 2014). All forms of land degradation lead to a reduction in or loss of urgently needed food for herbivores and additionally to a decline in the biodiversity of food plants (Harris et al., 2014; Murphy et al., 2016). Especially in areas with high seasonality, food availability changes rapidly and is highly related to annual rainfall, especially for grasses. To help monitor changes in food availability, remote sensing measuring techniques are a useful tool to provide us with data about food availability and quality on a large scale to manage the distribution of large herbivores, especially for wild-ranging herbivores and cattle. Nevertheless, herbivores' food selection is difficult and driven by various factors. For instance, our understanding of quality might not match the understanding of quality by a specific herbivore. For financial, technical, and logistical reasons, we tend to simplify feeding decisions in our efforts to manage the complex interactions and feeding systems of different herbivores and the plant response driven by feeding.

In the following we will give a short introduction of general nutritional concepts, feeding strategies, and the term *quality* as it relates to feeds, with a specific emphasis on ruminants, and then proceed to present different examples of our work.

Surrounded by a multidimensional feeding environment (as described in the overview chapter, Ramoelo et al., 2018), every animal has to search for the optimal food to obtain appropriate quantities of required nutrients, which usually vary by species. These nutrients are proteins, fat, carbohydrates, and to some extent minerals and vitamins. Moreover, an individual's underlying nutritional need varies not only with internal factors (e.g., age, body size, physiological aspects, life stage) but also with external factors such as weather conditions and season (see, e.g., Barboza et al., 2008; Robbins et al., 1987; Van Soest, 1994). Therefore, different individuals even within one species may select different types and amounts of food.

One of the biggest obstacles in our understanding of the food selection of herbivores, however, is that nutrients are available not as single item in one feeding bout but in a mixture of different items in one bite. For example, a high protein concentration in a food plant might be linked with high concentrations of toxic alkaloids (a group of plant secondary metabolites [PSMs]) or anything else. Therefore, animals most likely do not maximize one nutrient currency (e.g., select only one plant species as food because of its high nitrogen concentration) but instead balance their diet among different plant compounds not only to satisfy their nutritional needs (nutrient balancing; see Felton et al., 2016; Simpson & Raubenheimer, 2012; Westoby, 1974) but also to avoid negative effects such as toxification by PSMs (Freeland & Janzen, 1974) or over-ingestion of nutrients, which can also lead to detrimental health issues for the animal (Deutz et al., 2009; see also the info-box 'What Is Quality for a Ruminant?', Stolter et al., 2018). This balancing act is often reflected by the ingestion of a high variety of food plants (so-called diet-mixing [Villalba et al., 2002]), which can be fulfilled only in a heterogeneous, diverse environment.

Different feeding strategies to exploit different food plants have resulted in morphological and physiological adaptations in herbivores. As ruminants are the most important group of herbivores to humans and also the largest group of wild large herbivores, we will focus on their food adaptations. Note that other animals (e.g., hindgut fermenters such as elephants and zebras) differ in their adaptations and will therefore differ in their food selection and their ability to digest specific food items. Because of differences in feeding strategies and consequently differences of the gastrointestinal tract, ruminants are subdivided into feeding guilds (nutritional phenotypes) defined by their favoured food: grazers (grass and roughage feeders), mixed-feeders (intermediate type) and browsers (concentrate selectors; e.g., Clauss et al., 2008; Hofmann, 1989). The classification of these guilds is not family-specific (e.g., bovids occur in all feeding guilds, and 'grazer' does not mean that the animal feeds exclusively on grass). Interestingly, as a consequence of differences in the chemistry of food plants ingested (grasses or herbs and trees), these feeding guilds can also be arranged in an order reflecting their ability to cope with PSMs, the so called avoidance–tolerance continuum, from grazers (lowest in tolerance) to browsers (higher in tolerance; Iason & Villalba, 2006).

In contrast to other animals, ruminants have developed a unique complex digestive system that enables them to live exclusively on plants. This ability makes ruminants favourable for domestication as they can convert indigestible plants into valuable products (e.g., meat, milk) for humans. A community of different symbionts (microbiome) located in the rumen foregut is responsible for the digestion of plant material that is indigestible to non-fermenting animals, as ruminants themselves do not produce enzymes to degrade typical plant compounds like cellulose (Stevens & Hume, 1998). By fermenting plant material, the microbiome provides its host with essential energy in the form of short-chain fatty acids (Van Soest, 1994) and, as soon as the symbionts flow out of the rumen, with an additional source of protein (Hofmann, 2010). Hence, in contrast to other animals, a ruminant lives only indirectly on the food ingested, depending to a great extent on what is provided from the symbiotic community. Therefore, feedback loops from its microbiome might be necessary for a ruminant to learn which food to ingest and which to avoid (Provenza, 1995). This diet-related microbial community is complex and has coevolved with food plants over millions of years.

We found different microbial communities and differences in their function in different herbivores adapted to the food they usually ingest (e.g., grasses, forbs, browse; Mao et al., 2013; Petri et al., 2013). Therefore, it is a challenge to determine the quality of food for large herbivores, as these animals are highly adapted to their natural food. Hence, our point of view on quality is driven mainly by overall general patterns but might not necessarily fit to the preferred food of a given herbivore (see also 'What Is Quality for a Ruminant?', Stolter, 2018).

In the following sections we will provide extended summaries of different projects conducted within different tasks of SASSCAL. We will focus not only on remote sensing as a useful tool for measuring food availability and quality on a large scale but also on the impact of human land management as well as the influence of climate change on these topics. The projects are not directly related and rather show different aspects of the main topic of food availability and quality.

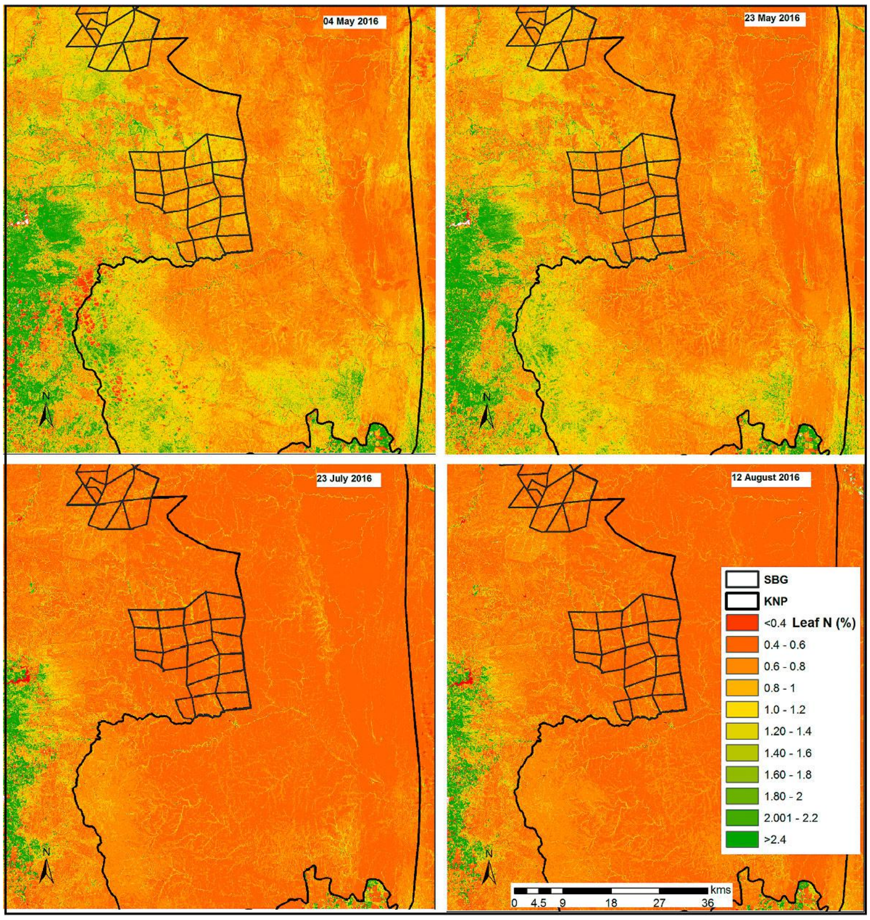

Figure 1: Spatial distribution of leaf nitrogen concentrations (%) as an indicator of grass quality in the Kruger National Park (KNP) and Sabie Sands Game Reserve (SGB) area (Ramoelo & Cho, 2018).

A. Remote sensing to estimate forage availability and quality projects

Introduction

Why is it important? Forage availability assessment is important to understand the state, extent, and quality of rangeland ecosystems. There are several indicators used to measure forage quantity and quality, of which biomass (mass per unit area) and grass or forage nitrogen (forage N) concentrations (indicator of protein content — that is, percentage of dry matter) are commonly used indicators. Forage quality and availability influence the movement and feeding patterns of herbivores including livestock (Ben-Shahar & Coe, 1992; Kaszta et al., 2016). A rapid increase in human population could result in land cover and land use changes that could continue to distress rangelands and food security through land degradation (FAO, 2010; Thornton, 2010). Land degradation is regarded as a threat to the productivity of rangelands (FAO, 2010). Degradation or loss of rangeland potential to provide grazing resources is also exacerbated by the ongoing global climate change phenomenon (Palmer & Bennett, 2013). Climate change induces erratic rainfalls and increases temperatures. As a result, disasters such as drought become prominent in Africa, affecting a high proportion of livestock production by reducing the availability and quality of grazing resources. Assessment of the quality of rangelands could provide information to inform decision-makers on planning and management. As an example, we visualized changes in leaf nitrogen concentration and annual grass biomass in the Kruger National Park between different seasons and years.

Methods

Assessment of forage availability and quality can be assessed using in situ or field-measured data. Remote sensing provides an alternative approach for mapping forage N and biomass for wider geographic areas and over time. The estimation of leaf N in grass has been successful using hyperspectral data derived from field spectrometers, airborne data (Knox et al., 2012; Mutanga & Skidmore, 2004; Ramoelo et al., 2013; Skidmore et al., 2010), and satellite remote sensing (Ramoelo et al., 2012; Ramoelo et al., 2015a). The mapping of forage N is possible because of the development of the second generation of vegetation indices based on the red edge wavelength, known to be positively related to chlorophyll and N (Cho & Skidmore, 2006; Curran et al., 1991) and narrow band indices (Mutanga & Skidmore, 2004; Mutanga & Skidmore, 2007; Ramoelo et al., 2012; Ramoelo et al., 2015a; Ramoelo et al., 2015b). Satellite sensors such as WorldView-2, RapidEye, and Sentinel-2 (freely available) have been successfully used to map grass N, and grass biomass has been successfully mapped since the 1970s using Landsat and, recently, MODIS sensors. Empirical regression analysis is often used to relate in situ measured grass N and biomass with vegetation indices derived from remote sensing images to create prediction

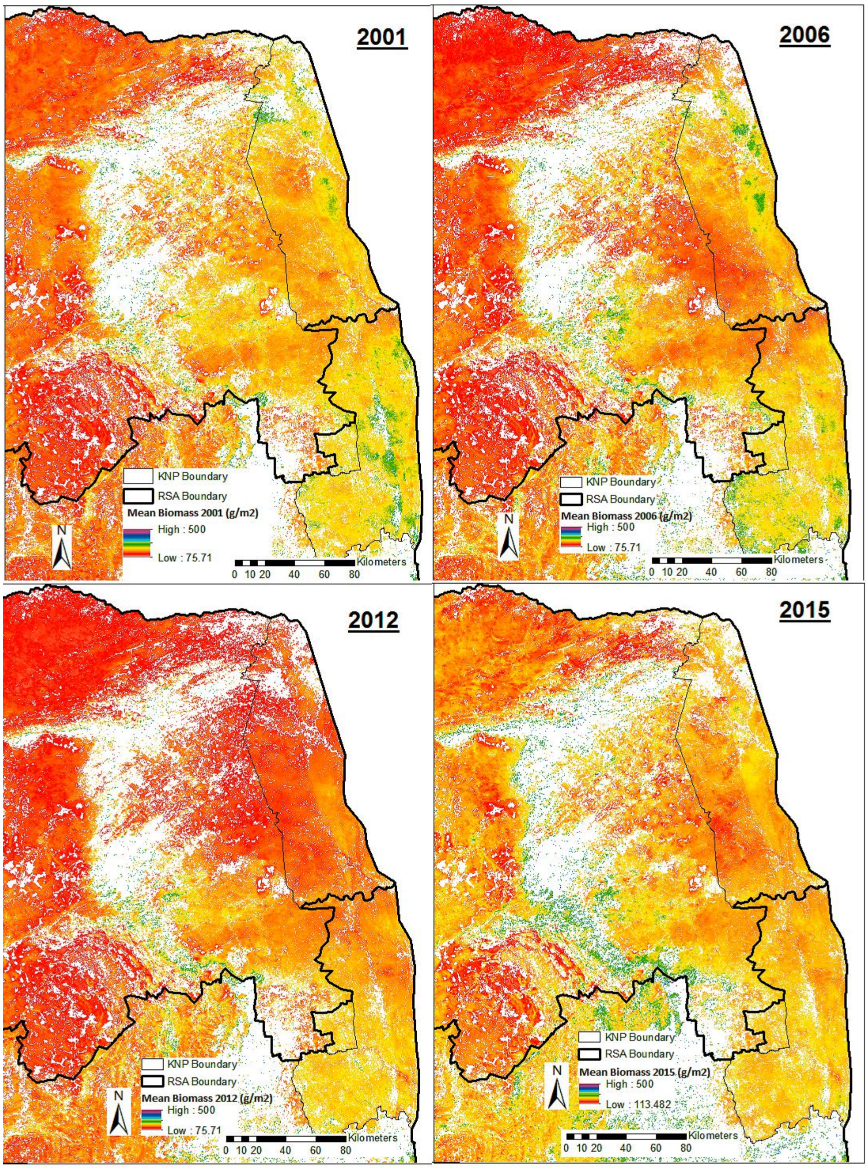

Figure 2: Spatial distribution of mean annual grass biomass (g/m2) in the KNP and surrounding areas (white spots are the masked areas of high tree densities based on the existing land cover).

models. Red edge–based indices were used to estimate leaf N, while leaf area index (LAI) was used to estimate grass biomass. We used empirical regression analysis and both Sentinel-2 and MODIS data to visualize changes in leaf nitrogen between different months (end of the wet season until end of the dry season) and changes in plant biomass among the years 2001, 2006, 2012, and 2015 for the Kruger National Park (South Africa) and surroundings.

Results

Figure 1 and 2 display forage N and biomass maps for the north-eastern part of South Africa, the Kruger National Park and surrounding areas. Red edge–based indices were used to estimate forage N and explained over 75% of leaf N variation. Grass biomass, on the other hand, was estimated using leaf area index (LAI), with the accuracy ranging between 50% and 80% for various dates. The results show clear patterns of grass or forage quality and availability, which are influenced by the underlying geological substrate. Forage quality and availability are also influenced by the frequency of fire (see also Joubert et al., 2018). The maps can be further analysed using any metric required.

Synthesis and outlook

Forage quality and biomass maps could be used as an input for the carrying capacity and stocking rates models for improved rangeland use planning and management. This could ideally reduce land degradation and loss of forage quality. Well-managed grazing areas improve livestock production and food security as well as game habitat utilization and movements, which are important for national parks and game farms. These products could further help in the analysis of how changes in climate influence current and future forage quality and availability (biomass).

B. Impacts on nutritional quality and plant availability

Impact of human land management on plant quality — general introduction

Large herbivores have an enormous impact on terrestrial ecosystems. Under different grazing pressures, vegetation composition and plant biomass might change (e.g., Olff & Ritchie, 1998; Parsons et al., 1994; Peco et al., 2006). Similarly, there could be changes in the chemical composition of plants as a result of feeding damage (e.g., Karban & Myers, 1989; Rooke & Bergström, 2007; Stolter, 2008; Stolter et al., 2005). In anthropogenic grazing systems, where cattle almost entirely substitute wild-ranging herbivores, natural long-distance movements are no longer possible because of the fragmented, often fenced-in landscape. In these areas, overgrazing is a challenge that has detrimental effects on the overall quality of a given habitat, such as by desertification or bush encroachment. Another land management activity that tends to influence the forage quality for both grazers (such as cattle, but also wild herbivores such as common warthog and gemsbok) and browsers (such as greater kudu, giraffe) is the long-held practice of bush burning. This leads to changes in the distribution of animals and consequently to changes in the utilization of an area. Therefore, we investigated the impacts and consequences of overgrazing, browsing, and fire in different projects. The following paragraphs will give extended summaries of these projects (for the influence of fire on plant quality and animal utilization, however, see Joubert et al. [2018] in this book).

Figure 3: Low and wide fences allow wild animals to move between sites.

Fence line and overgrazing

Introduction

Why is it important? Some large herbivores are known for their distinct migratory behaviour influenced by climatic conditions. These migrations often occur along the 'greening line' related to rainfall gradients in Africa or following the snowmelt gradients by large caribou and reindeer herds in Arctic regions. Migration allows herbivores in a seasonally changing environment to fulfil their nutritional needs by feeding on plants of higher quality (Fynn, 2012; Mårell et al., 2006). In addition, it gives already grazed areas time to recover from feeding damage. The naturally occurring migration pattern of some herbivores was adopted by humans during transhumance. With the development of settlements, however, the subdivision of land by fencing resulted in fragmented landscapes, especially when high fences supress every sort of migration and even small-scale movements. Inside the fence, herbivores might overutilize the available plant biomass, leading to changes in plant biodiversity as herbivores select the most palatable plants first (Skarpe, 1990) and changes in soil properties (Gröngröft et al., 2010), with consequences for the associated fauna (e.g., small herbivores, insects, reptiles). In our study (Kesch et al., in print), we determined the differences between areas with high and low grazing pressure using a fence-line contrast.

We determined how standing biomass of grass vegetation and its chemical characteristics differ between sites with low and high grazing pressure (for more details about the methods, see Kesch et al., in print). Furthermore, we determined how much time pasture in heavily grazed areas needs to recover from overgrazing effects.

Methods

Changes in vegetation composition and biomass can be easily seen along fence lines (e.g., along the Khutse Game Reserve in Botswana, where cattle replaced migratory wildlife). Three sampling sites were installed in three different areas, with one intensively grazed by livestock, one that had previously been intensively grazed but that at time of sampling was no longer used by livestock, and one site with low grazing pressure by wildlife. At each site, 21 sampling plots (100 cm²) were installed. Plots were sampled at different times of the year and each plot was cut 5 cm above the ground; samples were pooled for each plot and used for chemical analyses (ADF, NDF, and nitrogen). For a detailed description of the methods, see Kesch et al. (in print).

Results

Interestingly, we found that as a result of the feeding activity of the cattle, the remaining regrowing grass contains higher percentages of protein (high grazing intensity: dry season 6.0 % and wet season 9.9% vs. low grazing intensity: dry season 3.5% and wet season 4.6%) and lower concentrations of ADF and NDF, especially in the wet season (e.g., 35.1% ADF at high grazing intensity vs. 46.1% at the low-grazing-intensity site). Hence, we find a higher general quality of grasses in the heavily grazed region. However, heavy grazing leads to a reduced plant biomass (3 g/100 cm² at high grazing intensity compared to 31 g/100 cm² at low grazing intensity sites measured in the wet season). Furthermore, a shift in vegetation composition was mirrored in a higher abundance of unpalatable plant species (e.g., elephants root, *Elephantorrhiza* spec.). The exclusion of livestock resulted in a rapid increase of grass biomass after one wet season (2 g/100 cm² vs. 15 g/100 cm²), but this was not related to remarkable changes in plant chemical composition (see also Kesch et al., in print).

Synthesis and outlook

The enhanced plant quality (in terms of higher protein concentration) after feeding damage is a phenomenon of plant response reported worldwide in different plant types (grasses: Fanselow et al., 2011; bushes: Stolter et al., 2005; trees: Fornara & Du Toit, 2007). Some grass species in particular are known to be able to compensate for tissue loss (Beaulieu et al., 1996; Hik & Jefferies, 1990), and this compensatory growth is related to higher protein content, as plants need enzymes for regrowth and photosynthesis shortly after damage (but see below for an example of different plant response). Here, we have to point out that plant response is a species-specific reaction to damage and the resulting changes might be very different. But, heavy grazing led to reduced grass biomass in our experiment and in consequence, the absolute amount of protein available per unit area was lower in areas with high than in areas with low grazing pressure. In areas without livestock, the relatively lower quality (in terms of protein content) was compensated by a high availability of biomass. This lower quality range might be suitable for herbivores adapted to lower plant quality (e.g., adapted sheep or herded goats in relatively low numbers). Their feeding damage might lead to a positive feedback loop, depending on the grass species and soil conditions, for subsequent grazers, as described for other herbivores (Hempson et al., 2015).

To prevent overgrazing and subsequent negative impacts such as bush encroachment and desertification in areas where cattle substitutes wild-ranging herbivores, it is necessary to implement rotating grazing systems and adapt stocking rates as well as using a combination of different wild and domestic herbivores for sustainable development (e.g., Dickhoefer et al., 2010; Zimmermann & Smit, 2010). Fences should be adapted to the animals' needs; for example, low and wide fences with an adequate distance to the soil are beneficial for the movement of wild herbivores (Fig. 3) but restrict the movement of cattle.

Bush encroachment: species-specific plant response to damage on seedlings

Introduction

Why is it important? Plants can react to damage in many different ways. These responses can change both plant morphology and plant nutritional quality. In the case of food plants, they might lead to either reutilization (if plant response leads to higher quality; e.g., Stolter, 2008) or avoidance (e.g., if plant response leads to higher concentrations of deterrent substances [PSM] such as phenolics, or mechanical defence such as thorns and spines; e.g., Milewski et al., 1991). In the case of a defensive plant response, damage to bush encroacher species can lead to a higher number of thorns, larger thorns, and higher concentrations of deterrent substances to deter animals from feeding, but also to a lower concentration in nutrients. Therefore, knowledge about plant response is important for developing management strategies for different stakeholders. Especially for bush encroacher species (e.g., different *Acacia* species), this knowledge will aid in understanding and managing the transformation of grassland into thickets of bushes. Furthermore, as some herbivores utilize these plants as a food resource, the animals' feeding choice might offer an opportunity to reduce bush encroacher species, especially if the plants are in the seedling stage. Therefore, we examined how bush encroacher species react to the damage of their top shoot (whether through mechanical cutting by mowing or feeding damage by herbivores) in the seedling stage. We investigated whether damage to top shoots will result in changes in plant chemistry (e.g., lower or higher nitrogen, tannin, or phenolic concentrations) and whether changes in a plant's chemical composition will influence the food choice of sheep or goats. Furthermore, we studied whether sheep or goats prefer to feed on plants with high protein content and avoid plants with high PSM (condensed tannins and total phenolics) concentrations.

Methods

To understand the plant response of important encroacher species, we investigated the plant response of seedlings of *Acacia mellifera* (*Senegalia mellifera*, blackthorn, swarthaak), *A. tortilis* (*Vachellia tortilis*, umbrella thorn acacia), *A. reficiencs* (*Vachellia reficiens*, red bark acacia, rooihak), and *Dichrostachy cinerea* (sicklebush) to top-shoot damage (simulated browsing) in a greenhouse experiment (n = 40 of each species, except *A. tortilis* [n = 20]). Six months after damage, we tested their palatability to sheep and goats (more details about the methods are found in the bush encroachment chapter by Stolter et al. [2018]). For chemical response, we analysed the leaves after simulation of feeding damage for nitrogen, different fibre fractions, condensed tannins, and total phenolics (see Stolter [2018] for more details about the chemistry of feeds). In this chapter we will focus on the chemical response of the plants; results concerning the morphological response and more information about the consequences for subsequent herbivores are also given in the chapter on bush encroachment (Stolter et al., 2018).

Results

Swarthaak (umbrella thorn acacia) had slightly lower concentrations of nitrogen in the leaves of damaged plants compared to control plants; this result was more pronounced for sicklebush (1.77% N in damaged plants vs. 2.23% N in control plants). In this sense, we can see a loss in general quality after damage. Nevertheless, none of the investigated species showed a defensive reaction (which would be reflected in a higher condensed tannins or total phenolic concentration). We detected no remarkable changes in plant chemistry in rooihak.

In a subsequent feeding trial, we tested the influence of the plant response on sheep and goats. Neither sheep nor goats showed differences in selection between previously damaged or undamaged plants (for more detailed information, see the bush encroachment chapter, Stolter et al., 2018). Unlike goats, the chosen sheep breed (Cameroon blackbelly) totally avoided all four plant species, whether the plants were damaged or not. To test whether sheep avoided the plants because of the plants' tannin content, we additionally sprayed the plants with a polyethylene glycol solution (a common method for blocking tannin bioactivity; e.g., Makkar et al., 1995; Silanikove et al., 1994) and offered these plants for another week. However, the sheep still refused to feed on any of the plants offered. Goats, on the other hand, did not discriminate between damaged and control plants and preferred neither the plant species with the highest nitrogen concentration (swarthaak, 3.69% N in leaves of control plants) nor that with the lowest concentration of PSMs (swarthaak has virtually no condensed tannins; 0.63% total phenolics in leaves of control plants). Instead, goats favoured sicklebush, which is lower in nitrogen (2.23% N in leaves of control plants) and higher in PSM concentration (condensed tannins: 1.06%, total phenolics: 1.95% in leaves of control plants) than the other tested bush encroachers (more detailed results will be published by Stolter & Joubert elsewhere).

Synthesis and outlook

In contrast to our expectations, our results show only a slight change in nitrogen, leading to a slightly lower overall plant quality, but no real defensive strategy (e.g., we did not find higher tannins

Figure 4: Open top chambers (OTC) on a bush-cleared site in the thornbush savanna in Namibia (Erichsfelde Farm).

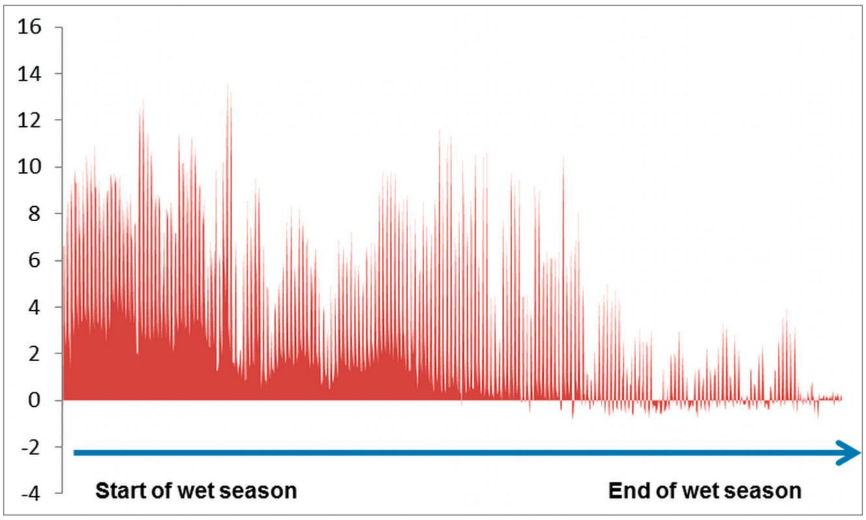

Figure 5: Differences in temperature in °C (y-axis) between inside the OTC and outside (mean of seven chambers per data point, 1,171 data points, measuring interval of 4 hours); time span (x-axis) from October (start of wet season) till May (end of wet season). Note: Differences were less at the end of the rainy season.

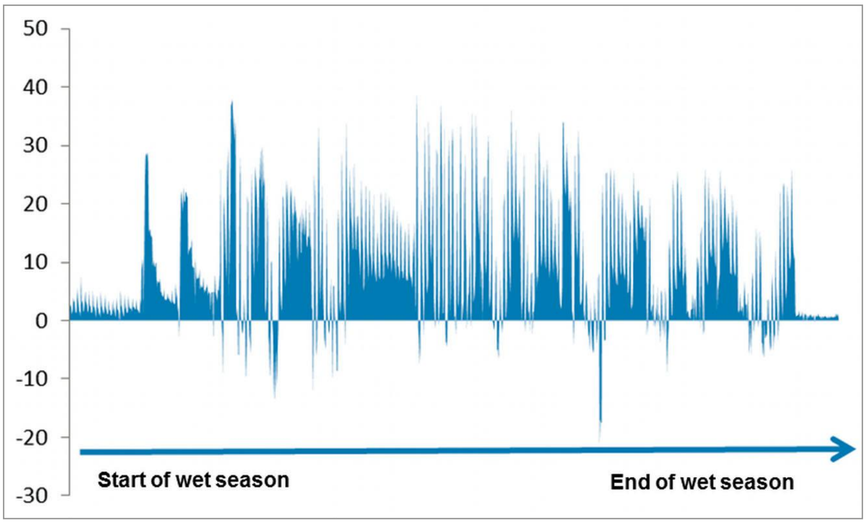

Figure 6: Reduction in relative humidity [%] inside the OTC chamber compared to the outside (y-axis, mean of seven chambers per data point, 1,171 data points, measuring interval of 4 hours); time span (x-axis) from October (start of wet season) till May (end of wet season). Note: There was no seasonally pronounced effect at the end of the rainy season compared to temperature.

content after damage). More interesting was our finding of a severe response in the morphological characteristics of the plants (see bush encroachment chapter, Stolter et al., 2018). Our feeding trial clearly demonstrated that neither do the measured PSMs lead to a total avoidance nor does the high nitrogen content lead to a feeding preference in goats. This result clearly underscores that food selection cannot be simplified to one food component but is rather a product of different trade-offs, as described by the nutrient-balance hypothesis (Felton et al., 2016; Simpson & Raubenheimer, 2012). In our case, food selection seemed to be driven not by plants' chemical content but by their morphological defences. This was related not to the size of the thorns but rather to their shape (Stolter et al., 2018). For management implications, however, the overall high quality of the plants might be interesting, as it is beneficial for herbivores that can cope with the mechanical barrier (e.g., kudu, goats) and the plants can also be used in a ground and pelleted form (to destroy the mechanical defence) as supplementary feeds for cattle. This utilization of these plant species as supplementary food can therefore contribute to the carrying capacity of the savanna ecosystem, especially in times of scarce food availability.

Impact of temperature and rainfall on plant chemical composition — general introduction

As a consequence of climatic changes, we can expect changes in the chemical compositions of plants that might lead to changes in food selection by herbivores. Studies on simulated climate change (e.g., increased temperature, reduced water availability, increased CO_2) lead to ambiguous results concerning changes in plant quality. For example, studies have shown that elevated CO_2 increases the assimilation of carbon. As a result, plant protein concentrations decrease, especially in dicotyledons used as food by browsers (Cotrufo et al., 1998), while concentrations of fibre and C-based PSMs (e.g., phenolics) might increase (Stiling & Cornelissen, 2007, but see Veteli et al., 2002). Furthermore, PSMs are known to be more toxic to mammals at higher ambient temperatures and detoxification costs can be enormous (Dearing, 2013; Forbey et al., 2013; Kurnath & Dearing, 2013).

As plant chemical composition is likely to change in response to climate change, the nutritional quality of feed will become a focal point of interest for different stakeholders (researchers, farmers, wildlife managers, nature conservationists, hunters) dealing with the management of large herbivores. To improve our understanding of climate change impacts, we investigated the influence of increased temperature and reduced humidity on the general plant quality of different grass species.

Methods

We installed 32 open-top chambers (OTC) in the thornbush savanna of Namibia (Fig. 4) for a period of seven months.

We used the i-botton data logger to measure differences in temperature and humidity between inside and outside every four hours (Fig. 5 and 6) to ensure that our OTC increased temperature and reduced humidity. For chemical analyses (nitrogen, different fibre fractions, ash), we used five grasses growing naturally in the area: *Pogonarthria fleckii* (annual hairy fishbone grass), *Urochloa brachyura*, *Melis repens* (red top), *Panicum* sp., and *Aristida stipitata* (bristlegrass) from inside and outside (control) the chambers.

Results

The mean difference in temperature between inside and outside the chambers was approximately 2.5°C; additionally, the humidity was reduced (Fig. 5 and 6). We found pronounced differences during the wet season for temperature but not for humidity. We found no significant differences in plant quality for four of our five species. Only bristlegrass showed higher concentrations of different fibre fractions as a result of a higher ADL content in the OTC chamber compared to control (NDF: 76.14% [OTC] vs. 74.68% [control]; ADF: 41.23% [OTC] vs. 39.73% [control]; ADL: 4.29% [OTC] vs. 3.89% [control]). More detailed results will be published by Stolter & Joubert elsewhere.

Synthesis and outlook

Our results indicate that the impact of higher temperature and lower humidity is species-specific. Four of the five tested species showed no difference while bristlegrass showed higher concentration of different fibre fractions mainly because of a higher concentration of ADL (an index of indigestible cell compounds such as lignins). This result indicates a reduction in quality for this species, whereas other grass species seem to be unaffected. More investigation concerning the plant response to changing climatic conditions would be beneficial in adapting management approaches for grassland systems such as by choosing specific adapted grass species for the reseeding of bush-cleared sites.

Conclusion

In this chapter we showed the results of in situ projects and an example of an application of remote sensing to study forage quality and quantity. Both techniques are of high value for developing management systems and enhancing expert knowledge about landscape utilization and management when it comes to large herbivores. Well-managed landscapes are of high importance for future livestock production, game farms, and nature conservation efforts. Knowledge gained from in situ projects (e.g., about changes in plant quality or food selection) are helpful for validating and developing large-scale remote-sensing models, which can improve rangeland planning and management. In this chapter we were able to show that plant responses to different types of damage (cattle grazing, top-shoot damage) and other factors (climate) are species-specific. However, we also demonstrated that food selection is dependent on the herbivore species, making generalizations regarding food quality potentially misleading. Consequently, detailed studies are necessary not only to understand the different impacts on food quality but also to understand the drivers of diet selection. We have a responsibility to transfer this gained knowledge from the laboratory to the field.

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References

Barboza, P.S., Parker, K.L. & Hume, I.D. (2008) *Integrative wildlife nutrition*. Springer Science & Business Media, Berlin.

Beaulieu, J., Gauthier, G. & Rochefort, L. (1996) The growth response of graminoid plants to goose grazing in a High Arctic environment. *Journal of Ecology*, 905–914.

Ben-Shahar, R. & Coe, M.J. (1992) The relationships between soil factors, grass nutrients and the foraging behaviour of wildebeest and zebra. *Oecologia*, **90**, 422–428.

Cho, M.A. & Skidmore, A.K. (2006) A new technique for extracting the red edge position from hyperspectral data: The linear extrapolation method. *Remote Sensing of Environment*, **101**, 181–193.

Clauss, M., Kaiser, T. & Hummel, J. (2008) The morphophysiological adaptations of browsing and grazing mammals. *The ecology of browsing and grazing*, pp. 47–88. Springer, Berlin.

Cotrufo, M.F., Ineson, P. & Scott, A. (1998) Elevated CO_2 reduces the nitrogen concentration of plant tissues. *Global Change Biology*, **4**, 43–54.

Curran, P.J., Dungan, J.L., Macler, B.A. & Plummer, S.E. (1991) The effect of a red leaf pigment on the relationship between red edge and chlorophyll concentration. *Remote Sensing of Environment*, **35**, 69–76.

Dearing, M.D. (2013) Temperature-dependent toxicity in mammals with implications for herbivores: a review. *Journal of Comparative Physiology B*, **183**, 43–50.

Deutz, A., Gasteiner, J. & Buchgraber, K. (2009) *Fütterung von Reh-und Rotwild: ein Praxisratgeber*. Stocker, Graz.

Dickhoefer, U., Buerkert, A., Brinkmann, K. & Schlecht, E. (2010) The role of pasture management for sustainable livestock production in semi-arid subtropical mountain regions. *Journal of Arid Environments*, **74**, 962–972.

Fanselow, N., Schönbach, P., Gong, X.Y., Lin, S., Taube, F., Loges, R., Pan, Q. & Dittert, K. (2011) Short-term regrowth responses of four steppe grassland species to grazing intensity, water and nitrogen in Inner Mongolia. *Plant and Soil*, **340**, 279–289.

FAO (Food and Agriculture Organization of the United Nations) (2010) Land degradation assessment in drylands (LADA). http://www.fao.org/nr/lada/ (accessed April 2017).

Felton, A.M., Felton, A., Raubenheimer, D., Simpson, S.J., Krizsan, S.J., Hedwall, P.-O. & Stolter, C. (2016) The nutritional balancing act of a large herbivore: an experiment with captive moose (*Alces alces L*). *PLOS One*, **11**, e0150870.

Forbey, J.S., Wiggins, N.L., Frye, G.G. & Connelly, J.W. (2013) Hungry grouse in a warming world: emerging risks from plant chemical defenses and climate change. *Wildlife Biology*, **19**, 374–381.

Fornara, D. & Du Toit, J. (2007) Browsing lawns? Responses of *Acacia nigrescens* to ungulate browsing in an African savanna. *Ecology*, **88**, 200–209.

Freeland, W.J. & Janzen, D.H. (1974) Strategies in herbivory by mammals: the role of plant secondary compounds. *The American Naturalist*, **108**, 269–289.

Fynn, R.W. (2012) Functional resource heterogeneity increases livestock and rangeland productivity. *Rangeland Ecology & Management*, **65**, 319–329.

Gröngröft, A., Mager, D., Medinski, T., Mills, A., Petersen, A. & Eschenbach, A. (2010). Evaluation of soil degradation state along fence-line contrasts. *Biodiversity in southern Africa. Vol. 2. Patterns and processes at regional scale*.pp. 207–213. Klaus Hess Publishers, Göttingen & Windhoek.

Harris, A., Carr, A. & Dash, J. (2014) Remote sensing of vegetation cover dynamics and resilience across southern Africa. *International Journal of Applied Earth Observation and Geoinformation*, **28**, 131–139.

Hempson, G.P., Archibald, S., Bond, W.J., Ellis, R.P., Grant, C.C., Kruger, F.J., Kruger, L.M., Moxley, C., Owen-Smith, N. & Peel, M.J. (2015) Ecology of grazing lawns in Africa. *Biological Reviews*, **90**, 979–994.

Hik, D. & Jefferies, R. (1990) Increases in the net above-ground primary production of a salt-marsh forage grass: a test of the predictions of the herbivore-optimization model. *The Journal of Ecology*, 180–195.

Hofmann, R.R. (1989) Evolutionary steps of ecophysiological adaptation and diversification of ruminants: a comparative view of their digestive system. *Oecologia*, **78**, 443-457.

Hofmann, R.R. (2010) *Wildtiere in Bildern zur vergleichenden Anatomie*. Schlütersche, Hannover.

Iason, G.R. & Villalba, J.J. (2006) Behavioral strategies of mammal herbivores against plant secondary metabolites: the avoidance–tolerance continuum. *Journal of Chemical Ecology*, **32**, 1115–1132.

Joubert, D.F., Stolter, C., Krewenka, K.M., Uunona, N., Amputu, V., Nghalipo, E., Thompson, S., Schütte, K., Kruspe, M., Throop, H., du Preez, P. Beytell, P., le Roux, M. & Aindongo, H. (2018) Impacts of fire history in a semi-arid woodland savanna. This volume.

Karban, R. & Myers, J.H. (1989) Induced plant responses to herbivory. *Annual Review of Ecology and Systematics*, **20**, 331–348.

Kaszta, Ż., Marino, J., Ramoelo, A. & Wolff, E. (2016) Bulk feeder or selective grazer: African buffalo space use patterns based on fine-scale remotely sensed data on forage quality and quantity. *Ecological Modelling*, **323**, 115–122.

Kesch, C., Stolter, C. & Ganzhorn, J.U. (in print). Changes in forage biomass and quality after exclusion of livestock in the southern Kalahari. *Ecotropica*.

Knox, N.M., Skidmore, A.K., Prins, H.H., Heitkönig, I.M., Slotow, R., van der Waal, C. & de Boer, W.F. (2012) Remote sensing of forage nutrients: Combining ecological and spectral absorption feature data. *ISPRS journal of Photogrammetry and Remote Sensing*, **72**, 27–35.

Kurnath, P. & Dearing, M.D. (2013) Warmer ambient temperatures depress liver function in a mammalian herbivore. *Biology Letters*, **9**, 20130562.

Lehmann, C.E.R., Ratnam, J. & Hutley, L. B. (2009) Which of these continents is not like the other? Comparisons of tropical savanna systems: key questions and challenges. *New Phytologist*, **181**, 508–511.

Mao, S., Zhang, R., Wang, D. & Zhu, W. (2013) Impact of subacute ruminal acidosis (SARA) adaptation on rumen microbiota in dairy cattle using pyrosequencing. *Anaerobe*, **24**, 12–19.

Makkar, H.P.S., Blümmel, M. & Becker, K. (1995). Formation of complexes between polyvinyl pyrrolidones or polyethylene glycols and tannins, and their implication in gas production and true digestibility in in vitro techniques. *British Journal of Nutrition*, **73**, 897–913.

Mårell, A., Hofgaard, A. & Danell, K. (2006) Nutrient dynamics of reindeer forage species along snowmelt gradients at different ecological scales. *Basic and Applied Ecology*, **7**, 13–30.

Milewski, A.V., Young, T.P. & Madden, D. (1991) Thorns as induced defenses: experimental evidence. *Oecologia*, **86**, 70–75.

Murphy, B.P., Andersen, A.N. & Parr, C.L. (2016) The underestimated biodiversity of tropical grassy biomes. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **371**, 20150319.

Mutanga, O. & Skidmore, A. (2004) Integrating imaging spectroscopy and neural networks to map grass quality in the Kruger National Park, South Africa. *Remote Sensing of Environment*, **90**, 104–115.

Mutanga, O. & Skidmore, A.K. (2007) Red edge shift and biochemical content in grass canopies. *ISPRS Journal of Photogrammetry and Remote Sensing*, **62**, 34–42.

Olff, H. & Ritchie, M.E. (1998) Effects of herbivores on grassland plant diversity. *Trends in Ecology & Evolution*, **13**, 261–265.

Palmer, A.R. & Bennett, J.E. (2013) Degradation of communal rangelands in South Africa: towards an improved understanding to inform policy. *African Journal of Range & Forage Science*, **30**, 57–63.

Parsons, A., Newman, J., Penning, P., Harvey, A. & Orr, R. (1994) Diet preference of sheep: effects of recent diet, physiological state and species abundance. *Journal of Animal Ecology*, 465–478.

Peco, B., Sánchez, A.M. & Azcárate, F.M. (2006) Abandonment in grazing systems: consequences for vegetation and soil. *Agriculture, Ecosystems & Environment*, **113**, 284–294.

Petri, R.M., Schwaiger, T., Penner, G.B., Beauchemin, K.A., Forster, R.J., McKinnon, J.J. & McAllister, T.A. (2013) Characterization of the core rumen microbiome in cattle during transition from forage to concentrate as well as during and after an acidotic challenge. *PLOS One*, **8**, e83424.

Provenza, F.D. (1995) Postingestive feedback as an elementary determinant of food preference and intake in ruminants. *Journal of Range Management Archives*, **48**, 2–17.

Ramoelo, A. & Cho, M. A. (2018) Explaining leaf nitrogen distribution in a semi-arid environment predicted on Sentinel-2 imagery using a field spectroscopy derived model. *Remote Sensing*, **10**, 269.

Ramoelo, A., Cho, M.A., Mathieu, R., Madonsela, S., Van De Kerchove, R., Kaszta, Z. & Wolff, E. (2015a) Monitoring grass nutrients and biomass as indicators of rangeland quality and quantity using random forest modelling and WorldView-2 data. *International Journal of Applied Earth Observation and Geoinformation*, **43**, 43–54.

Ramoelo, A., Cho, M., Mathieu, R. & Skidmore, A.K. (2015b) Potential of Sentinel-2 spectral configuration to assess rangeland quality. *Journal of Applied Remote Sensing*, **9**, 094096–094096.

Ramoelo, A., Skidmore, A., Cho, M.A., Mathieu, R., Heitkönig, I., Dudeni-Tlhone, N., Schlerf, M. & Prins, H. (2013) Non-linear partial least square regression increases the estimation accuracy of grass nitrogen and phosphorus using in situ hyperspectral and environmental data. *ISPRS Journal of Photogrammetry and Remote Sensing*, **82**, 27–40.

Ramoelo, A., Skidmore, A.K., Cho, M.A., Schlerf, M., Mathieu, R. & Heitkönig, I.M. (2012) Regional estimation of savanna grass nitrogen using the red-edge band of the space-borne RapidEye sensor. *International Journal of Applied Earth Observation and Geoinformation*, **19**, 151–162.

Ramoelo, A., Stolter, C., Joubert, D.F., Cho, M.A., Groengroeft, A., Madibela, O.R., Zimmermann, I. & Pringle, H. (2018) Rangeland monitoring and assessment: overview. This volume.

Robbins, C., Hanley, T., Hagerman, A., Hjeljord, O., Baker, D., Schwartz, C. & Mautz, W. (1987) Role of tannins in defending plants against ruminants: reduction in protein availability. *Ecology*, **68**, 98–107.

Rooke, T. & Bergström, R. (2007) Growth, chemical responses and herbivory after simulated leaf browsing in *Combretum apiculatum*. *Plant Ecology*, **189**, 201–212.

Simpson, S.J. & Raubenheimer, D. (2012) *The nature of nutrition: a unifying framework from animal adaptation to human obesity*. Princeton University Press, Princeton, NJ, USA.

Silanikove, N., Nitsan, Z. & Perevolotsky, A. (1994) Effect of a daily supplementation of poly (ethylene glycol) on intake and digestion of tannin-containing leaves (*Ceratonia siliqua*) by sheep. *Journal of Agricultural and Food Chemistry*, **42**, 2844–2847.

Skarpe, C. (1990) Shrub layer dynamics under different herbivore densities in an arid savanna, Botswana. *Journal of Applied Ecology*, 873–885.

Skidmore, A.K., Ferwerda, J. G., Mutanga, O., Van Wieren, S.E., Peel, M., Grant, R.C., Prins, H.H., Balcik, F.B. & Venus, V. (2010) Forage

Rangelands

quality of savannas – Simultaneously mapping foliar protein and polyphenols for trees and grass using hyperspectral imagery. *Remote Sensing of Environment*, **114**, 64–72.

Stevens, C.E. & Hume, I.D. (1998) Contributions of microbes in vertebrate gastrointestinal tract to production and conservation of nutrients. *Physiological Reviews*, **78**, 393–427.

Stiling, P. & Cornelissen, T. (2007) How does elevated carbon dioxide (CO2) affect plant–herbivore interactions? A field experiment and meta-analysis of CO2-mediated changes on plant chemistry and herbivore performance. *Global Change Biology*, **13**, 1823–1842.

Stolter, C. (2008) Intra-individual plant response to moose browsing: feedback loops and impacts on mulitple consumers. *Ecological Monographs*, **78**, 167–183.

Stolter, C. (2018) What is quality for a ruminant? A short introduction to the meaning of plant chemical composition measurements. This volume.

Stolter, C., Ball, J.P., Julkunen-Tiitto, R., Lieberei, R. & Ganzhorn, J.U. (2005) Winter browsing of moose on two different willow species: food selection in relation to plant chemistry and plant response. *Canadian Journal of Zoology*, **83**, 807–819.

Stolter, C., Joubert, D.F., Schwarz, K. & Finckh, M. (2018) Two different issues of bush encroachment management: plant response and animal distribution. This volume.

Thornton, P.K. (2010) Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **365**, 2853–2867.

Van Soest, P.J. (1994) *Nutritional ecology of the ruminant*. Cornell University Press, Ithaca, NY, USA.

Veteli, T., Kuokkanen, K., Julkunen-Tiitto, R., Roininen, H. & Tahvanainen, J. (2002) Effects of elevated CO_2 and temperature on plant growth and herbivore defensive chemistry. *Global Change Biology*, **8**, 1240–1252.

Villalba, J.J., Provenza, F.D. & Bryant, J. (2002) Consequences of the interaction between nutrients and plant secondary metabolites on herbivore selectivity: benefits or detriments for plants? *Oikos*, **97**, 282–292.

Westoby, M. (1974) An analysis of diet selection by large generalist herbivores. *The American Naturalist*, **108**, 290–304.

Zimmermann, I. & Smit, G.N. (2010) Impact of landuse at landscape scale, using fenceline contrasts and a best-practice case study. *Biodiversity in Southern Africa. Vol. 2. Patterns and processes at regional scale.* pp.214–221. Klaus Hess Publishers, Göttingen & Windhoek.

References [CrossRef]

Barboza, P.S., Parker, K.L. & Hume, I.D. (2008) *Integrative wildlife nutrition*. Springer Science & Business Media, Berlin.

Beaulieu, J., Gauthier, G. & Rochefort, L. (1996) The growth response of graminoid plants to goose grazing in a High Arctic environment. *Journal of Ecology*, 905–914. CrossRef

Ben-Shahar, R. & Coe, M.J. (1992) The relationships between soil factors, grass nutrients and the foraging behaviour of wildebeest and zebra. *Oecologia*, **90**, 422–428. CrossRef

Cho, M.A. & Skidmore, A.K. (2006) A new technique for extracting the red edge position from hyperspectral data: The linear extrapolation method. *Remote Sensing of Environment*, **101**, 181–193. CrossRef

Clauss, M., Kaiser, T. & Hummel, J. (2008) The morphophysiological adaptations of browsing and grazing mammals. *The ecology of browsing and grazing*, pp. 47–88. Springer, Berlin. CrossRef

Cotrufo, M.F., Ineson, P. & Scott, A. (1998) Elevated CO2 reduces the nitrogen concentration of plant tissues. *Global Change Biology*, **4**, 43–54. CrossRef

Curran, P.J., Dungan, J.L., Macler, B.A. & Plummer, S.E. (1991) The effect of a red leaf pigment on the relationship between red edge and chlorophyll concentration. *Remote Sensing of Environment*, **35**, 69–76. CrossRef

Dearing, M.D. (2013) Temperature-dependent toxicity in mammals with implications for herbivores: a review. *Journal of Comparative Physiology B*, **183**, 43–50. CrossRef

Deutz, A., Gasteiner, J. & Buchgraber, K. (2009) *Fütterung von Reh-und Rotwild: ein Praxisratgeber*. Stocker, Graz.

Dickhoefer, U., Buerkert, A., Brinkmann, K. & Schlecht, E. (2010) The role of pasture management for sustainable livestock production in semi-arid subtropical mountain regions. *Journal of Arid Environments*, **74**, 962–972. CrossRef

Fanselow, N., Schönbach, P., Gong, X.Y., Lin, S., Taube, F., Loges, R., Pan, Q. & Dittert, K. (2011) Short-term regrowth responses of four steppe grassland species to grazing intensity, water and nitrogen in Inner Mongolia. *Plant and Soil*, **340**, 279–289. CrossRef

FAO (Food and Agriculture Organization of the United Nations) (2010) Land degradation assessment in drylands (LADA). http://www.fao.org/nr/lada/ (accessed April 2017).

Felton, A.M., Felton, A., Raubenheimer, D., Simpson, S.J., Krizsan, S.J., Hedwall, P.-O. & Stolter, C. (2016) The nutritional balancing act of a large herbivore: an experiment with captive moose (*Alces alces L*). *PLOS One*, **11**, e0150870. CrossRef

Forbey, J.S., Wiggins, N.L., Frye, G.G. & Connelly, J.W. (2013) Hungry grouse in a warming world: emerging risks from plant chemical defenses and climate change. *Wildlife Biology*, **19**, 374–381. CrossRef

Fornara, D. & Du Toit, J. (2007) Browsing lawns? Responses of *Acacia nigrescens* to ungulate browsing in an African savanna. *Ecology*, **88**, 200–209. CrossRef

Freeland, W.J. & Janzen, D.H. (1974) Strategies in herbivory by mammals: the role of plant secondary compounds. *The American Naturalist*, **108**, 269–289. CrossRef

Fynn, R.W. (2012) Functional resource heterogeneity increases livestock and rangeland productivity. *Rangeland Ecology & Management*, **65**, 319–329. CrossRef

Gröngröft, A., Mager, D., Medinski, T., Mills, A., Petersen, A. & Eschenbach, A. (2010). Evaluation of soil degradation state along fence-line contrasts. *Biodiversity in southern Africa. Vol. 2. Patterns and processes at regional scale*.pp. 207–213. Klauss Hess Publishers, Göttingen & Windhoek.

Harris, A., Carr, A. & Dash, J. (2014) Remote sensing of vegetation cover dynamics and resilience across southern Africa. *International Journal of Applied Earth Observation and Geoinformation*, **28**, 131–139. CrossRef

Hempson, G.P., Archibald, S., Bond, W.J., Ellis, R.P., Grant, C.C., Kruger, F.J., Kruger, L.M., Moxley, C., Owen-Smith, N. & Peel, M.J. (2015) Ecology of grazing lawns in Africa. *Biological Reviews*, **90**, 979–994. CrossRef

Hik, D. & Jefferies, R. (1990) Increases in the net above-ground primary production of a salt-marsh forage grass: a test of the predictions of the herbivore-optimization model. *The Journal of Ecology*, 180–195. CrossRef

Hofmann, R.R. (1989) Evolutionary steps of ecophysiological adaptation and diversification of ruminants: a comparative view of their digestive system. *Oecologia*, **78**, 443-457. CrossRef

Hofmann, R.R. (2010) *Wildtiere in Bildern zur vergleichenden Anatomie*. Schlütersche, Hannover.

Iason, G.R. & Villalba, J.J. (2006) Behavioral strategies of mammal herbivores against plant secondary metabolites: the avoidance–tolerance continuum. *Journal of Chemical Ecology*, **32**, 1115–1132. CrossRef

Joubert, D.F., Stolter, C., Krewenka, K.M., Uunona, N., Amputu, V., Nghalipo, E., Thompson, S., Schütte, K., Kruspe, M., Throop, H., du Preez, P. Beytell, P., le Roux, M. & Aindongo, H. (2018) Impacts of fire history in a semi-arid woodland savanna. This volume. CrossRef

Karban, R. & Myers, J.H. (1989) Induced plant responses to herbivory. *Annual Review of Ecology and Systematics*, **20**, 331–348. CrossRef

Kaszta, Ż., Marino, J., Ramoelo, A. & Wolff, E. (2016) Bulk feeder or selective grazer: African buffalo space use patterns based on fine-scale remotely sensed data on forage quality and quantity. *Ecological Modelling*, **323**, 115–122. CrossRef

Kesch, C., Stolter, C. & Ganzhorn, J.U. (in print). Changes in forage biomass and quality after exclusion of livestock in the southern Kalahari. *Ecotropica*.

Knox, N.M., Skidmore, A.K., Prins, H.H., Heitkönig, I.M., Slotow, R., van der Waal, C. & de Boer, W.F. (2012) Remote sensing of forage nutrients: Combining ecological and spectral absorption feature data. *ISPRS journal of Photogrammetry and Remote Sensing*, **72**, 27–35. CrossRef

Kurnath, P. & Dearing, M.D. (2013) Warmer ambient temperatures depress liver function in a mammalian herbivore. *Biology Letters*, **9**, 20130562. CrossRef

Lehmann, C.E.R., Ratnam, J. & Hutley, L. B. (2009) Which of these continents is not like the other? Comparisons of tropical savanna systems: key questions and challenges. *New Phytologist*, **181**, 508–511. CrossRef

Mao, S., Zhang, R., Wang, D. & Zhu, W. (2013) Impact of subacute ruminal acidosis (SARA) adaptation on rumen microbiota in dairy cattle using pyrosequencing. *Anaerobe*, **24**, 12–19. CrossRef

Makkar, H.P.S., Blümmel, M. & Becker, K. (1995). Formation of complexes between polyvinyl pyrrolidones or polyethylene glycols and tannins, and their implication in gas production and true digestibility in in vitro techniques. *British Journal of Nutrition*, **73**, 897–913. CrossRef

Mårell, A., Hofgaard, A. & Danell, K. (2006) Nutrient dynamics of reindeer forage species along snowmelt gradients at different ecological scales. *Basic and Applied Ecology*, **7**, 13–30. CrossRef

Milewski, A.V., Young, T.P. & Madden, D. (1991) Thorns as induced defenses: experimental evidence. *Oecologia*, **86**, 70–75. CrossRef

Murphy, B.P., Andersen, A.N. & Parr, C.L. (2016) The underestimated biodiversity of tropical grassy biomes. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **371**, 20150319. CrossRef

Mutanga, O. & Skidmore, A. (2004) Integrating imaging spectroscopy and neural networks to map grass quality in the Kruger National Park, South Africa. *Remote Sensing of Environment*, **90**, 104–115. CrossRef

Mutanga, O. & Skidmore, A.K. (2007) Red edge shift and biochemical content in grass canopies. *ISPRS Journal of Photogrammetry and Remote Sensing*, **62**, 34–42. CrossRef

Olff, H. & Ritchie, M.E. (1998) Effects of herbivores on grassland plant diversity. *Trends in Ecology & Evolution*, **13**, 261–265. CrossRef

Palmer, A.R. & Bennett, J.E. (2013) Degradation of communal rangelands in South Africa: towards an improved understanding to inform policy. *African Journal of Range & Forage Science*, **30**, 57–63. CrossRef

Parsons, A., Newman, J., Penning, P., Harvey, A. & Orr, R. (1994) Diet preference of sheep: effects of recent diet, physiological state and species abundance. *Journal of Animal Ecology*, 465–478. CrossRef

Peco, B., Sánchez, A.M. & Azcárate, F.M. (2006) Abandonment in grazing systems: consequences for vegetation and soil. *Agriculture, Ecosystems & Environment*, **113**, 284–294. CrossRef

Petri, R.M., Schwaiger, T., Penner, G.B., Beauchemin, K.A., Forster, R.J., McKinnon, J.J. & McAllister, T.A. (2013) Characterization of the core rumen microbiome in cattle during transition from forage to concentrate as well as during and after an acidotic challenge. *PLOS One*, **8**, e83424. CrossRef

Provenza, F.D. (1995) Postingestive feedback as an elementary determinant of food preference and intake in ruminants. *Journal of Range Management Archives*, **48**, 2–17. CrossRef

Ramoelo, A. & Cho, M. A. (2018) Explaining leaf nitrogen distribution in a semi-arid environment predicted on Sentinel-2 imagery using a field spectroscopy derived model. *Remote Sensing*, **10**, 269. CrossRef

Ramoelo, A., Cho, M.A., Mathieu, R., Madonsela, S., Van De Kerchove, R., Kaszta, Z. & Wolff, E. (2015a) Monitoring grass nutrients and biomass as indicators of rangeland quality and quantity using random forest modelling and WorldView-2 data. *International Journal of Applied Earth Observation and Geoinformation*, **43**, 43–54. CrossRef

Ramoelo, A., Cho, M., Mathieu, R. & Skidmore, A.K. (2015b) Potential of Sentinel-2 spectral configuration to assess rangeland quality. *Journal of Applied Remote Sensing*, **9**, 094096–094096. CrossRef

Ramoelo, A., Skidmore, A., Cho, M.A., Mathieu, R., Heitkönig, I., Dudeni-Tlhone, N., Schlerf, M. & Prins, H. (2013) Non-linear partial least square regression increases the estimation accuracy of grass nitrogen and phosphorus using in situ hyperspectral and environmental data. *ISPRS Journal of Photogrammetry and Remote Sensing*, **82**, 27–40. CrossRef

Ramoelo, A., Skidmore, A.K., Cho, M.A., Schlerf, M., Mathieu, R. & Heitkönig, I.M. (2012) Regional estimation of savanna grass nitrogen using the red-edge band of the spaceborne RapidEye sensor. *International Journal of Applied Earth Observation and Geoinformation*, **19**, 151–162. CrossRef

Ramoelo, A., Stolter, C., Joubert, D.F., Cho, M.A., Groengroeft, A., Madibela, O.R., Zimmermann, I. & Pringle, H. (2018) Rangeland monitoring and assessment: overview. This volume. CrossRef

Robbins, C., Hanley, T., Hagerman, A., Hjeljord, O., Baker, D., Schwartz, C. & Mautz, W. (1987) Role of tannins in defending plants against ruminants: reduction in protein availability. *Ecology*, **68**, 98–107. CrossRef

Rooke, T. & Bergström, R. (2007) Growth, chemical responses and herbivory after simulated leaf browsing in *Combretum apiculatum*. *Plant Ecology*, **189**, 201–212. CrossRef

Simpson, S.J. & Raubenheimer, D. (2012) *The nature of nutrition: a unifying framework from animal adaptation to human obesity*. Princeton University Press, Princeton, NJ, USA. CrossRef

Silanikove, N., Nitsan, Z. & Perevolotsky, A. (1994) Effect of a daily supplementation of poly (ethylene glycol) on intake and digestion of tannin-containing leaves (*Ceratonia siliqua*) by sheep. *Journal of Agricultural and Food Chemistry*, **42**, 2844–2847. CrossRef

Skarpe, C. (1990) Shrub layer dynamics under different herbivore densities in an arid savanna, Botswana. *Journal of Applied Ecology*, 873–885. CrossRef

Skidmore, A.K., Ferwerda, J. G., Mutanga, O., Van Wieren, S.E., Peel, M., Grant, R.C., Prins, H.H., Balcik, F.B. & Venus, V. (2010) Forage quality of savannas — Simultaneously mapping foliar protein and polyphenols for trees and grass using hyperspectral imagery. *Remote Sensing of Environment*, **114**, 64–72. CrossRef

Stevens, C.E. & Hume, I.D. (1998) Contributions of microbes in vertebrate gastrointestinal tract to production and conservation of nutrients. *Physiological Reviews*, **78**, 393–427. CrossRef

Stiling, P. & Cornelissen, T. (2007) How does elevated carbon dioxide (CO2) affect plant–herbivore interactions? A field experiment and meta-analysis of CO2-mediated changes on plant chemistry and herbivore performance. *Global Change Biology*, **13**, 1823–1842. CrossRef

Stolter, C. (2008) Intra-individual plant response to moose browsing: feedback loops and impacts on mulitple consumers. *Ecological Monographs*, **78**, 167–183. CrossRef

Stolter, C. (2018) What is quality for a ruminant? A short introduction to the meaning of plant chemical composition measurements. This volume. CrossRef

Stolter, C., Ball, J.P., Julkunen-Tiitto, R., Lieberei, R. & Ganzhorn, J.U. (2005) Winter browsing of moose on two different willow species: food selection in relation to plant chemistry and plant response. *Canadian Journal of Zoology*, **83**, 807–819. CrossRef

Stolter, C., Joubert, D.F., Schwarz, K. & Finckh, M. (2018) Two different issues of bush encroachment management: plant response and animal distribution. This volume. CrossRef

Thornton, P.K. (2010) Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **365**, 2853–2867. CrossRef

Van Soest, P.J. (1994) *Nutritional ecology of the ruminant*. Cornell University Press, Ithaca, NY, USA.

Veteli, T., Kuokkanen, K., Julkunen-Tiitto, R., Roininen, H. & Tahvanainen, J. (2002) Effects of elevated CO_2 and temperature on plant growth and herbivore defensive chemistry. *Global Change Biology*, **8**, 1240–1252. CrossRef

Villalba, J.J., Provenza, F.D. & Bryant, J. (2002) Consequences of the interaction between nutrients and plant secondary metabolites on herbivore selectivity: benefits or detriments for plants? *Oikos*, **97**, 282–292. CrossRef

Westoby, M. (1974) An analysis of diet selection by large generalist herbivores. *The American Naturalist*, **108**, 290–304. CrossRef

Zimmermann, I. & Smit, G.N. (2010) Impact of landuse at landscape scale, using fenceline contrasts and a best-practice case study. *Biodiversity in Southern Africa. Vol. 2. Patterns and processes at regional scale.* pp.214–221. Klauss Hess Publishers, Göttingen & Windhoek.

What is quality for a ruminant? A short introduction to the meaning of plant chemical composition measurements

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The “quality” of a given food item depends on the morphological adaptations and physiological requirements of the animal (Stolter et al., 2018). For ruminants the digestion of feeds by the microbiome is essential, therefore food selection is an indirect process. As a result, determining of the drivers behind food selection (e.g. plant quality) is a challenging issue. Nevertheless, some general assumptions about quality can be made:

Energy

It has often been assumed that animals should select for energy-rich food to gain the most benefit of a selected food item in combination with the lowest costs for searching. Energy can be derived from different nutrients. Even though fat gives the most energy, for herbivores energy originates mainly from fibre (mainly cellulose and hemicellulose, see van Soest, 1994), as plants are rich in fibre but low in fat and protein content; energy is gained in an indirect way. In the case of ruminants, most energy is delivered as small chain fatty acids produced by the symbionts of the microbiome in the rumen fermenting different fibre fractions. Therefore, the most common species of this microbiome represent primary degraders (e.g., of cellulose, hemicellulose; Wallace, 2008) due to the natural food of herbivores. This way of digestion is a special adaptation for feeding on plants and is different to that of other animals (such as carnivores or omnivores). This type of feeding must therefore be taken into account when we think of “high quality” food for a ruminant. For example, protein- or carbohydrate-rich feeds are generally expected to be of high nutritional value. Caution must be taken, however, in giving “easily digestible” feeds that contain high concentrations of soluble carbohydrates such as starch (e.g., in grain and corn), low-molecular-weight carbohydrates (e.g., sugar rich fruits), and high amounts of protein to ruminants that are not able to balance the over-ingestion of unfamiliar food (e.g., ruminants in captivity or animal fed with supplementary feeds in the wild). These highly unbalanced diets can lead to detrimental effects on the microbiome such as rumen acidosis or alkalosis (Deutz et al., 2009; Mao et al., 2013) with strong negative effects on animals ranging from diarrhoea to sudden death (sepsis, resulting from excessive loss of rumen symbionts).

Energy is often measured as total or gross energy (e.g., by using calorimetric bombs. It is important to note, however, that these measurements do not distinguish between digestible and indigestible compounds (e.g., indigestible wood will give nearly the same energy content as digestible leaves).

Fibre and other carbohydrates

Fibre is a term that describes the structural carbohydrates of plant cells, which are mainly hemicellulose and cellulose. Lignin, which belongs chemically to the phenolics (a group of plant secondary metabolites), is normally included in this group of compounds. Even though soluble carbohydrates (e.g., sugar, starch) are much easier to digest, ruminants have adapted to digest hemicellulose and cellulose. As mentioned above, feeding high concentrations of soluble carbohydrates can lead to fatal consequences for ruminants, in contrast, the end products (small-chain fatty acids) of the fermentation of hemicellulose and cellulose provide up to 80% of the required energy for the animal (Barboza et al., 2008), while lignin is almost indigestible (Van Soest, 1994). Often food with “high fibre” concentration is assumed to be of “low quality” mainly because of long retention times in the digestive system. As part of the adaptation of ruminants to fibrous feeds, however, the retention time in the rumen is supposed to be long, because rumen symbionts simply need time for fermentation. Differences in the concentrations of fibre fractions in different food plants (e.g. grasses

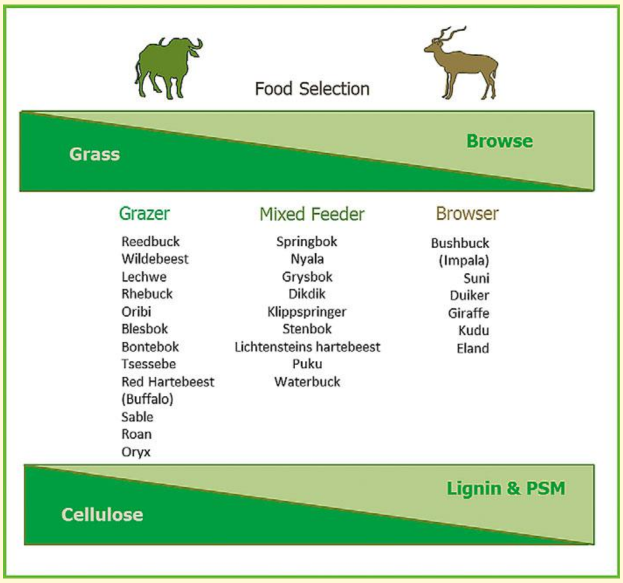

Figure 1. Examples of different feeding types of ruminants, their food selection, and the amount of cellulose, PSM and lignin in their diets, which is related to their tolerance and / or ability to ingest and digest these food items. Note, that grazers do not live exclusively on grasses, nor do browsers feed exclusively on browse.

vs. browse) have led to diverse morphological and physiological adaptations in ruminants resulting in different feeding types (Fig 1). Furthermore, the microbiome of ruminants confronted with different fibre concentrations during different seasons, will react by changing the composition and function of the symbiontic community (Sundset et al., 2009).

Similar to energy, "fibre" is a mixture of different compounds and therefore different fibre fractions can be analysed, e.g. the detergent fibre analysis, Van Soest analysis. Here the plant cell material is divided into soluble cell and cell wall constituents (NDF, ADF and ADL are given; see Fig. 2 for further explanations).

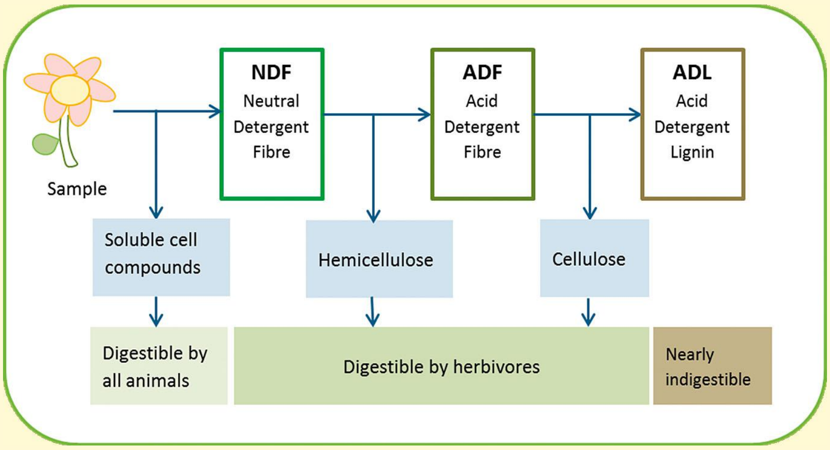

Figure 2. Explanation of the van Soest analyses for fibre. During these analyses different plant constituents are washed out (soluble cell compounds, hemicellulose, cellulose) while NDF, ADF, and ADL remain. A high NDF value can indicate either easily digestible soluble compounds, digestible cellulose and hemicellulose or a high concentration of indigestible lignin. As a consequence, assumptions about "general quality" can be gained only by comparing each fraction or by calculating the differences between NDF, ADF and ADL.

Protein

Protein, often indexed by the nitrogen concentration in the food, is indeed an important nutrient. The general low level of protein in plants, compared to meat, has led to the assumption that herbivores are limited in protein and therefore should maximize their protein intake (e.g. protein maximization hypothesis, see Mattson, 1980) and consequently select plants with high protein concentrations. However, ruminants have evolved physiological adaptations to overcome this problem. Instead of excreting large amounts of nitrogen via urea, ruminants have a recycling system that enables them to transfer metabolic nitrogen back into the rumen, where the microbial symbionts are able to use this nitrogen to build body´s own microbial amino acids which are the basic elements of protein. After their lifetime the microbes are frequently washed from the rumen into lower parts of the gastrointestinal tract, where they are digested and the amino acids of the protein are absorbed (Barboza et al., 2008). This process might be beneficial as non-organic nitrogen from urea is already transferred into amino acids by the rumen microbes. The amino acids can be used by the ruminant to form body´s own protein, instead of building amino acids by themselves in the first step (see also Madibela et al., 2018).

Minerals – The importance of other sources

Minerals are very important for the health of herbivores, e.g. for the development of their skeleton and for muscle contractions, nerve tissue metabolism, and immune response (Barboza et al., 2008; Robbins, 2012). The ingestion of minerals (e.g. Ca, P, Na, Cl, K, Mg, S, Co, Cu, I, Fe, Mn, Se, Zn) is essential, as animals are not able to produce minerals by themselves. Plants are not especially mineral rich and the concentration and composition of a certain food plant does not match the requirements of the foraging animals. Therefore, herbivores often use non-food resources to satisfy their needs. This use has been observed for many mammals, e.g. geophagy by elephants and primates and visits to human latrines by two-toed sloths (Krishnamani & Mahaney, 2000; Holdø et al., 2002; Heymann et al., 2011).

Plant secondary metabolites (PSMs)

PSMs have been assumed to have negative effects on diet selection of mammals due to their toxicity or deterrent effects (Freeland & Janzen, 1974; Bryant & Kuropat, 1980). However, the composition of specific compounds and their effects are not well understood. Our understanding is still hampered by the mostly unknown chemical structures and the lack of analyses to measure the bioactivity of these compounds (see also Rautio et al., 2007; Salminen & Karonen, 2011).

The effects on the animal are largely depending on the dose (Villalba et al. 2002), on the type of compound ingested, on other ingested food compounds and on the adaptation of the herbivore. There is an increasing tolerance to PSMs in general along the gradient from grazers to browsers (Iason & Villalba, 2006, see Fig 1.). In principal, the physiological effects of PSMs can be distinguished by their mode of action, e.g., deterrence by smell or taste, inhibitory effects of digestion or high toxicity (e.g. Hagerman et al., 1992; Stolter et al., 2005; Edlich & Stolter, 2012). The latter might have the highest priority as drivers of diet selection. But in contrast to some domestic animals, wild ruminants can often discriminate toxic plants. Detoxification of specific PSM is often related to a specific pathway. If diets of generalist herbivores are restricted to single species this detoxification

Rangelands

pathway might be blocked by ingesting high amounts of a certain PSM (Freeland & Janzen, 1974; Marsh et al., 2006). Consequently, especially for generalists it can be advantageous to consume a multi-species diet (Foley & Moore, 2005). If animals have to live on a restricted diet (e.g. during dry seasons or winter), the only possibility to overcome this bottleneck might be selectivity for low concentrations of PSM as avoidance is simply not possible (Stolter et al., 2013). However, PSMs do not only appear to have negative effects on the consuming animal, but beneficial effects of their ingestion have also been identified.

In particular tannins are known to interact with nutrients such as protein und carbohydrates by building complexes assumed to reduce the quality of the ingested food (e.g. Makkar et al., 1988; Lorenz et al., 2014; but see Salminen & Karonen, 2011). On the other hand, animals on restricted or inappropriate, unbalanced diets (e.g. supplementary feeding, captivity, or livestock) will profit from this complex binding capacity of tannins, e.g. by binding over-ingested carbohydrates or protein. Furthermore, tannins can have various positive effects on ruminants, such as the reduction of internal parasites, increasing milk production, and the reduction of the risk of bloat (Min et al., 2003; Lyman et al., 2008). These contradictions between positive and negative effects might be explained by the differences in chemical structure as the term “tannins” describes a large group of different substances and every plant species has its own composition. More information about tannins is given in Madibela et al. (2018).

References

Barboza, P. S., Parker, K. L., & Hume, I. D. (2008). *Integrative wildlife nutrition*. Springer Science & Business Media, Berlin.

Bryant, J. P., & Kuropat, P. J. (1980). Selection of winter forage by subarctic browsing vertebrates: the role of plant chemistry. *Annual Review of Ecology and Systematics*, **11**, 261-285.

Deutz, A., Gasteiner, J., & Buchgraber, K. (2009). *Fütterung von Reh-und Rotwild: ein Praxisratgeber*; Stocker, Graz.

Edlich, S. C., & Stolter, C. (2012). Effects of essential oils on the feeding choice by moose. *Alces,* **48**, 17-25.

Foley, W. J., & Moore, B. D. (2005). Plant secondary metabolites and vertebrate herbivores–from physiological regulation to ecosystem function. *Current Opinion in Plant Biology,* **8**, 430-435.

Freeland, W. J. & Janzen, D. H. (1974). Strategies in herbivory by mammals: the role of plant secondary compounds. *The American Naturalist,* **108**, 269-289.

Hagerman, A. E., Robbins, C. T., Weerasuriya, Y., Wilson, T. C., & McArthur, C. (1992). Tannin chemistry in relation to digestion. *Journal of Range Management,* **45**, 57-62.

Heymann, E. W., Amasifuén, C. F., Tello, N. S., Herrera, E. R. T., & Stojan-Dolar, M. (2011). Disgusting appetite: Two-toed sloths feeding in human latrines. *Mammalian Biology-Zeitschrift für Säugetierkunde,* **76**, 84-86.

Holdø, R. M., Dudley J. P., & McDowell. L. R. (2002). Geophagy in the African elephant in relation to availability of dietary sodium. *Journal of Mammalogy,* **83**, 652-664.

Iason, G. R., & Villalba, J. J. (2006). Behavioral strategies of mammal herbivores against plant secondary metabolites: the avoidance–tolerance continuum. *Journal of Chemical Ecology,* **32**, 1115-1132.

Krishnamani, R., & Mahaney, W. C. (2000). Geophagy among primates: adaptive significance and ecological consequences. *Animal Behaviour,* **59**, 899-915.

Lorenz, M. M., Alkhafadji, L., Stringano, E., Nilsson, S., Mueller-Harvey, I., & Udén, P. (2014). Relationship between condensed tannin structures and their ability to precipitate feed proteins in the rumen. *Journal of the Science of Food and Agriculture,* **94**, 963-968.

Lyman, T. D., Provenza, F. D., & Villalba, J. J. (2008). Sheep foraging behavior in response to interactions among alkaloids, tannins and saponins. *Journal of the Science of Food and Agriculture,* **88**, 824-831.

Makkar, P., Dawra, R., & Singh, B. (1988). Determination of both tannin and protein in a tannin-protein complex. *Journal of Agricultural and Food Chemistry,* **36**, 523-525.

Mao, S., Zhang, R., Wang, D., & Zhu, W. (2013). Impact of subacute ruminal acidosis (SARA) adaptation on rumen microbiota in dairy cattle using pyrosequencing. *Anaerobe,* **24**, 12-19.

Madibela, O. R., Kemiso, D., & Kwedibana, J. (2018). Quality of wild herbaceous legumes and ist role in livestock nutrition. This volume.

Marsh, K. J., Wallis, I. R., Andrew, R. L., & Foley, W. J. (2006). The detoxification limitation hypothesis: where did it come from and where is it going? *Journal of Chemical Ecology,* **32**, 1247-1266.

Mattson, Jr, W. J. (1980). Herbivory in relation to plant nitrogen content. *Annual Review of Ecology and Systematics,* **11**, 119-161.

Min, B., Barry, T., Attwood, G., & McNabb, W. (2003). The effect of condensed tannins on the nutrition and health of ruminants fed fresh temperate forages: a review. *Animal Feed Science and Technology,* **106**, 3-19.

Rautio, P., Bergvall, U., Karonen, M., & Salminen, J.-P. (2007). Bitter problems in ecological feeding experiments: commercial tannin preparations and common methods for tannin quantifications. *Biochemical Systematics and Ecology,* **35**, 257-262.

Robbins, C. (2012). *Wildlife feeding and nutrition*. Elsevier, Amsterdam.

Salminen, J. P., & Karonen, M. (2011). Chemical ecology of tannins and other phenolics: we need a change in approach. *Functional Ecology,* **25**, 325-338.

Stolter, C., Ball, J. P., Julkunen-Tiitto, R., Lieberei, R., & Ganzhorn, J. U. (2005). Winter browsing of moose on two different willow species: food selection in relation to plant chemistry and plant response. *Canadian Journal of Zoology,* **83**, 807-819.

Stolter, C., Ball, J. P., & Julkunen-Tiitto, R. (2013). Seasonal differences in the relative importance of specific phenolics and twig morphology result in contrasting patterns of foraging by a generalist herbivore. *Canadian Journal of Zoology,* **91**, 338-347.

Stolter, C., Ramoelo, A., Kesch, K., Madibela, O., Cho, M. A., & Joubert, D. (2018). Forage quality and availability for large herbivores in southern African rangelands. This volume.

Sundset, M. A., Edwards, J. E., Cheng, Y. F., Senosiain, R. S., Fraile, M. N., Northwood, K. S., Præsteng, K. E, Glad, T., Mathiesen, S. D., & Wright, A.-D. G. (2009). Rumen microbial diversity in Svalbard reindeer, with particular emphasis on methanogenic archaea. *Fems Microbiology Ecology,* **70**, 553-562.

Van Soest, P. J. (1994). *Nutritional ecology of the ruminant*. Cornell University Press. Ithaca, New York.

Villalba, J. J., Provenza, F. D., & Bryant, J. (2002). Consequences of the interaction between nutrients and plant secondary metabolites on herbivore selectivity: benefits or detriments for plants? *Oikos,* **97**, 282-292.

Wallace, R. J. (2008). Gut microbiology–broad genetic diversity, yet specific metabolic niches. *Animal*, **2**, 661-668.

Open-access database – HERBFEEDS on nutritional quality of food plants for herbivores

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Figure 1: Wild hindgut fermenter (zebra) meeting domestic foregut fermenters (cattle). Nutritional quality is one important aspect for understanding the habitat selection of wild herbivores (Image: S. Baumann).

Large herbivores contribute the lion's share of the gross national product in southern Africa. Main parts of the grassland ecosystems are used for livestock and game farming. Additionally, wild-ranging large herbivores are main attractants for tourism, providing an increasing contribution to the economy, and they are of high value for nature conservation. Next to animal husbandry, "bush meat" (including sport hunting) is an important food resource in southern Africa. It is expected that under the pressure of future human population growth, the pressure on wild and domestic herbivores will intensify. In this context, knowledge about the nutritional values of different food plants seems to be indispensable and of high importance for different stakeholders, ranging from the management of land use (e.g., livestock and game farming) to the management of wildlife conservation. Therefore, SASSCAL aims to create an open-access database on the nutritional quality of food plants.

As a result of the high availability and utilization of grasses, we have good information about grass quality. In contrast, less information is available about shrubs, trees, and herbs. These plants are often utilized by browsers but are also an alternative or supplementary food resource for livestock, especially in times of restricted food availability. It can be assumed that as a result of changes in climate, the importance of these food resources will be even more pronounced. We therefore aim to include different life forms of plants in the database (for an example, see Table 1).

The database will contain information on different nutrients, energy concentrations, and plant secondary metabolites. Furthermore, differences in analyses, either in the methodology or in the solvent used, will be included, as the applied methodology and the solvent used may lead to differences in the measured concentrations. The different fibre fractions

Table 1: Example of the structure of the database

Species	Other names	Plant life form	Ref. or Analyzer	Location	Biome	Time of sampling	Plant part	Nitrogen [%]	NDF [%]	ADF [%]	ADL [%]	Ash [%]	Condensed Tannins [%]		......
														Extraction & Method	......
Grewia flava	Brandy-bush, velvet raisin	Bush	SASSCAL Stolter & Toma-schewski	Waterberg, Namibia	Savanna	End of rainy season	Top shoots including leaves	2.8	45.6	66.5	6.5	6.6	1.23	Methanol Butanol-HCl	......
Leucosphaera bainesii	Wolbos, perdebossie, silverbossie	Shrub	SASSCAL Stolter & Toma-schewski	Erichsfelde, Namibia	Savanna	Rainy season	Top shoots including leaves	1.3	49.7	29.2	6.3	8.6	0	Methanol Butanol-HCl	......
Eragrostis contortus	Lehmann lovegrass	Grass	Kesch et al. (accepted)	Khutse and Central Kalahari Game Reserve, Botswana	Savanna	Combined samples	Whole plants	3.1	78.2	43.5	-	-	-	-	....

(neutral detergent fibre (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL)) will be given to index the concentration of soluble cell compounds, hemicellulose, and cellulose (for details, see info box on nutritional quality in this book (Stolter, 2018)). Because of seasonal and intra-individual differences in chemical composition, we will also include information on the season when sampling occurred and about the part of the plant analysed and the herbivore feeding on the plant, if applicable.

As mentioned in the section on forage availability and quality (Stolter et al., 2018), the quality of a given food item depends on physiological requirements, which vary by animal species; morphological adaptation to the food (e.g., hindgut or foregut fermenter); body size; age; sex; life stage (e.g., reproductive state); etc. Therefore, the database gives only nutritional values and insights into the "general quality" but offers no conclusions about the quality of feeds for specific herbivores.

Inputs into the database are gained either from fieldwork and lab analyses or from other data resources. Contributions that add valuable information to the database are welcome and should be sent to herbivorefeeds@sasscal.org. Planned linkages with other databases such as the Photo Guide to the Plants of Southern Africa (Hillmann et al., 2018) will expand the given information.

References

Hillmann, T., Muche, G., Josenhans, K., & Jürgens, N. (2018). SASSCAL photo guide to plants of southern Africa. This volume.

Stolter, C. (2018). What is quality for a ruminant? A short introduction to the meaning of plant chemical composition measurements. This volume.

Stolter, C., Ramoelo, A., Kesch, K., Madibela, O., Cho, M.A. & Joubert, D. (2018). Forage quality and availability for large herbivores in southern African rangelands. This volume.

Rangelands

Quality of wild herbaceous legumes and its role in livestock nutrition

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Abstract: Climate change in southern Africa is predicted to be severe, and animal agriculture will suffer the most. However, there exist wild legumes that have survived under harsh environmental conditions and contribute to a varied diet for the grazing ungulates. This study tested the chemical composition of four wild herbaceous legumes each from Tswapong and Ngamiland districts in Botswana (*Chamaecrista abscus, Chamaecrista rotundifolia, Crotalaria sphaerocarpa, Tephrosia lupinifolia, Tephrosia purpurea, Indigofera* sp., *Zornia glochidiata*.). These plant species were previously found to fix nitrogen in the soil by the SASSCAL research Task 316, and the plant selection was also guided by informed focus discussions with farmers. For Tswapong the results show that *C. rotundifolia* and *T. purpurea* had the highest level of crude protein (CP) while *Z. glochidiata* had the least CP. In vitro gas production showed high gas yield for *Z. glochidiata*, and a small volume of gas was produced by *T. lupinifolia*. Condensed tannins (CT) were higher for *Z. glochidiata* and *C. rotundifolia* but lower for *T. purpurea and T. lupinifolia*. CT were at similar concentration for *C. rotundifolia* and *Z. glochidiata*. No relationship was detected between condensed tannins and crude protein. With regard to samples from Ngamiland, there was no differences among plant species for acid detergent fibre (ADF), whereas other parameters measured were significantly different among the legume plants. *Indigofera sp*. had the highest CP, while *Crotalaria sphaerocarpa* had the lowest. In general, levels of crude protein were different among the legumes investigated but overall were higher than in natural grass, indicating their importance in providing protein to grazing ungulates in rangelands. Their high protein content also suggests the plants' potential as protein supplements if domesticated as fodder crops. However, palatability, toxicity, and intake should be tested in future studies before any recommendations are made.

Resumo: Prevê-se que as alterações climáticas no Sul de África sejam severas, e a agricultura animal será a que irá sofrer mais. Porém, existem leguminosas silvestres que sobreviveram sob condições ambientais severas e contribuem para uma dieta variada dos ungulados de pastagem. Este estudo testou a composição química de quatro leguminosas herbáceas silvestres, cada uma dos distritos de Tswapong e Ngamiland no Botswana (*Chamaecrista abscus, Chamaecrista rotundifolia, Crotalaria sphaerocarpa, Tephrosia lupinifolia, Tephrosia purpurea, Indigofera* sp., *Zornia glochidiata*). Foi previamente descoberto pela equipa de trabalho 316 do SASSCAL que estas espécies de plantas fixam azoto no solo, tendo a selecção de plantas sido também guiada por discussões de foco informado com agricultores. Para Tswapong, os resultados mostram que *C. rotundifolia* e *T. purpurea* tiveram os níveis mais elevados de proteína bruta (CP), enquanto que *Z. glochidiata* teve a menor quantidade de CP. In vitro, a produção de gás mostrou um elevado rendimento pela Z. *glochidiata*, enquanto que um pequeno volume de gás foi produzido pela *T. lupinifolia*. Taninos condensados (CT) foram mais elevados na *Z. glochidiata* e *C. rotundifolia*, mas menos elevados na *T. purpurea* e *T. lupinifolia*. Os CT tinham concentrações semelhantes na *C. rotundifolia* e *Z. glochidiata* Nenhuma relação foi detectada entre os taninos condensados e a proteína bruta. Em relação às amostras de Ngamiland, não houve diferenças entre as espécies de plantas em relação à fibra detergente ácida (ADF), enquanto que outros parâmetros medidos foram significativamente diferentes entre as plantas leguminosas. *Indigofera sp*. teve a maior CP, enquanto que *Crotalaria sphaerocarpa* teve a menor. No geral, os níveis de proteína bruta foram diferentes entre as espécies de leguminosas investigadas, mas globalmente foram maiores que em gramíneas naturais, indicando a sua importância no fornecimento de proteína aos ungulados em pastagens. O seu elevado conteúdo de proteína sugere também o potencial das plantas como suplemento de proteína se domesticadas como culturas forrageiras. No entanto, a palatabilidade, toxicidade e ingestão deverão ser testadas em estudos futuros antes de serem feitas quaisqueres recomendações.

Introduction

With the advent of climate change and prolonged dry periods, grazing ungulates will face challenges in terms of meeting their nutrient requirements for maintenance, growth, reproduction, and immunity. Prior to the arrival of these challenges and constraints, both livestock and wildlife have survived in harsh arid and semi-arid environments thanks to their unique utilization of rangeland resources. Their adaptation to fluctuations in forage quality, especially nitrogen levels, has resulted in the evolution of a nitrogen conservation mechanism, especially in ruminants, through the recycling of scarce nitrogen back into their digestive systems. This has prepared these animals to be fit for these particular environments (Wilson, 2009). Even though the animals evolved in rangelands with supposedly low nutritive value, in reality these rangelands do contain some plant species with high nutritive value. Nevertheless, the plants also contain anti-nutritive attributes from having adapted to the grazing by herbivores. These plant species such as herbaceous legumes have higher nutritive value compared to grasses. In the wild, these herbaceous and shrubby legumes (Fig. 1) contribute to dietary diversity and supply needed nutrients to meet requirements for the maintenance, growth, reproduction, and immune function of grazing animals in rangelands. Some species grow spontaneously in ploughed fields, thus fertilising the soil through nitrogen fixation and as green fertiliser when ploughed in (Bernard et al., 2017; Obopile et al., 2018). In most cases, the importance of such plant species is not appreciated until there is drought or a long dry period. With increasing feed shortages in the rangelands resulting from the effects of climate change, therefore, herbaceous legumes will become even more important. To formulate better strategies for their utilisation, however, wild legumes need to be characterised and suitable ones identified.

Utilisation of shrubby wild legumes has been recognised in improving ruminant production elsewhere; for example, one legume in Indonesia, *Indigofera arrecta,* was identified as a potential fodder plant. It was found to produce as much as 28 tons of dry matter per hectare per year with a high protein content of 27–29% and dry matter digestibility ranging between 67% and 81% (Abdullah & Kumalarasi, 2011). However, wild legumes have also been observed to contain condensed tannins (CT). Compounds such as condensed tannins, alkaloids, and saponins, commonly called secondary metabolites, act as natural defence of trees and plants against herbivores and pests (Stolter, 2018). In terms of the nutrition of grazing animals, CT can have both beneficial and detrimental effects on animals' health and digestion, depending on the concentration and structure of condensed tannins. At lower concentrations of less than 5 g/kg, condensed tannins bind with proteins, reducing their degradation in the rumen (Hoste et al., 2012). After the tannin-protein complex has dissociated in the acidic environment of the abomasum (Naumann et al., 2014), however, protein becomes available to the small intestine (Tedeschi et al., 2014). This will result in an increase in the supply and absorption of essential amino acids (Waghorn et al., 1987), benefiting growth, milk production, and immune function. On the other hand, high CT concentrations in the diets of grazing ungulates compromise palatability, voluntary intake, digestibility, and nitrogen retention (Silanikove et al., 2001). Other research (Jensen, 2012; Lamy et al., 2011) has reported that grazing plants containing tannins modulate grazing behaviour, and the motive for grazing plants with high secondary compounds may be to achieve physiological homeostasis, which could be viewed as self-medication (Stolter et al., 2018; Villalba & Landau, 2012). Therefore, to understand the contributions of different wild herbaceous legumes to the nutrition of grazing livestock in rangelands and arable lands, their nutritive value must be determined. This process should also involve the quantification of secondary metabolites. This will enable formulation of effective and sustainable as well as ecologically and environmentally sound utilisation of rangelands (Lamy et al., 2011) and the use of legumes as protein supplements or their adoption as fodder crops. Some plant species studied here were found to fix nitrogen (Bernard et al., 2017), others grow in arable fields, and others were observed to have been browsed; their selection was also partly guided by informed focus discussions with farmers in the studied areas (results not shown). Therefore, this study was carried out to determine the nutritive value and to quantify the amount of condensed tannins in wild herbaceous legumes in two ecological regions of Botswana. This study is part of the larger study sponsored by SASSCAL, and the plants studied are among a consortium of herbaceous plants investigated by Task 316 (Making use of the wild legume resource to improve arable and livestock farming in Botswana).

Materials and methods

Sample collection and analysis

Three to four plants per species were obtained by random sampling from rangelands in two districts of Ngamiland and Tswapong in Botswana except *Chamaecrista* spp., which were obtained from arable lands. Sites of sampling were previously described by Bernard et al. (2017). The sampled species were *Chamaecrista rotundifolia*, *Tephrosia purpurea*, *Tephrosia lupinifolia,* and *Zornia glochidiata* in Tswapong district and *Chamaecrista abscus, Indigofera* sp., *Crotalaria sphaerocarpa,* and *Tephrosia* sp. in Ngamiland, sampled during the flowering stage. The genus *Tephrosia* belongs to the Leguminosae family, and according to Chen et al. (2014) many of the species have important traditional uses in agriculture because they possess the bioactivity of phytoalexins. *Chamaecrista rotundifolia* was previously described by Tarawali (1995) as having potential for mixed legume pastures and having good dry matter productivity, excellent seed production, and persistence. According to Hassen et al. (2018), *Indigofera* sp. display excellent adaptation to a range of environments and possess diverse morphological and agronomic attributes significant to their use as forage and cover crops. Identification was done in the field and at the Botswana University of Agriculture and Natural Resources (BUAN) Herbarium and

Figure 1: Images showing a few of the herbaceous plants used in this study: (a) *Chamaecrista abscus*, (b) *Zornia glochidiata*, (c) *Crotalaria sphaerocarpa*. Photos: O.R. Madibela.

the Botswana National Herbarium and Botanic Gardens in Gaborone (Bernard et al., 2017). The plants were selected as guided by informed group discussions with farmers from the two regions (data not shown) and also by the abundance of certain plants in the localities. Samples were cut at 5 cm above ground level and transported to the laboratory, where samples from the same plant were pooled together before drying in an oven set at 60°C for 48 hours. After drying the samples were milled to pass through a 3 mm sieve.

Chemical Analysis

Dry matter, ash, acid detergent fibre (ADF), neutral detergent fibre (NDF), and crude protein were determined according to standard methods of AOAC (1996). For detailed description of these parameters, refer to the info box "What Is Quality for a Ruminant?" by Stolter (2018). *Lablab purpureus* is a common fodder crop among small-scale livestock farmers in southern Africa and therefore was used as a control. However, this was done only for samples from Tswapong.

Condensed tannins and gas production

Only samples from Tswapong were also tested for condensed tannins according to Makkar (2000) and expressed as leucocyanidin equivalents. Total gas production of the Tswapong samples was determined after incubation of a sample with rumen fluid in glass syringes according to modified methods of Menke & Steingass (1988) to index digestibility.

Data analysis

Data from the two sites were not compared because of differences in the plant species sampled. This is because the same plants were not found growing at the two sites. Differences in the nutritive value of the sampled species were tested by analysis of variance (ANOVA) using general linear models (GLM) implemented in SAS (2002–2008), and results are reported as least-square means ± standard error of mean (SEM). A simple correlation analysis between crude protein and condensed tannins was tested using Pearson (SAS, 2002–2008).

Table 1: Differences in chemical composition (g/kg) and in vitro gas production (ml/0.5 g) of different wild legumes species from Tswapong. DM = dry matter; CP = crude protein; NDF = neutral fibre; CT = condensed tannins; SEM = standard error of mean

Plants	DM	Ash	CP	NDF	CT	Gas
Chamaecrista rotundifolia	974	188	324	481	2.53	35
Tephrosia purpurea	969	246	374	342	0.46	35
Tephrosia lupinifolia	968	170	200	260	0.61	22
Zornia glochidiata	971	145	184	533	2.68	55
Lablab purpureus	965	100	240	431	2.4	72
SEM	03.1	21.4	13.7	69.0	1.09	4.74
P-value	NS	*	***	NS	NS	**

Table 2: Differences in chemical composition (g/kg) of different wild legume species from Ngamiland. DM = dry matter; ADF = acid detergent fibre; NDF = neutral detergent fibre; CP = crude protein; SEM = standard error of mean

Parameters	DM	Ash	CP	ADF	NDF
Chamaecrista abscus	940.0	306.5	226.8±24.9	229.5	362.5
Crotalaria sphaerocarpa	930.0	128.0	159.8±24.9	142.0	316.0
Indigofera sp.	930.0	152.0	362.5±35.2	96.5	268.5
Tephrosia sp.	950.0	132.0	343.0±24.9	174.5	362.5
SEM	8.7	12.9		22.7	12.8
P-value	NS	**	*	NS	*

Results

The nutritive value of wild legumes from Tswapong is shown in Table 1. There was no difference in NDF or condensed tannins concentration among the legumes. *C. rotundifolia* and *T. purpurea* had the highest CP while *Zornia glochidiata* had the least. No correlation (r = –0.26; P = 0.53) was detected between condensed tannins and crude protein.

Results from samples from Ngamiland are presented in Table 2. There was a tendency (P = 0.057) toward variations in ADF levels among plant species, while other parameters differed (from $P < 0.01$ to $P < 0.05$) among the legume plants.

Discussion

Chemical composition

Crude protein (CP), which is generally used as an index of quality in ruminant diets, averaged 270.4 g/kg for plants from Tswapong, with *Tephrosia purpurea* having the highest concentration of CP and *Zornia glochidiata* having the lowest. Legumes from Ngamiland had an average CP of 273.0 g/kg, with *Indigofera* sp. having the highest levels and *Crotalaria sphaerocarpa* having the lowest. These concentrations of CP are similar to and/or better than that of *Lablab purpureus*, a fodder crop commonly offered to livestock in small-holder farm in southern Africa. However, the apparently high CP levels in the wild herbaceous legumes species compared to most fodder plants may be misleading, as the high toxic amino acids and other plant nitrogenous secondary metabolites could mean that animals would either not consume the material or not utilise it effectively (Hassen et al., 2008). The availability of protein in sufficient amounts to the animal is controlled by feed intake and ease of digestion by rumen microorganisms and the animal's own enzymes. Therefore, the issue of the biomass yield of these legumes is important for consideration for future utilisation as fodder crops for livestock. In addition, high fibre/lignin content binding to the protein may be detrimental to the availability of the protein, and according to Stolter et al. (2018), these factors will also negatively affect feed intake and other feeding activities. Therefore, future work with these herbaceous plants should investigate the extent of bonding of lignin and other anti-nutritive compounds with protein. Ash content for samples from Tswapong was high for *Tephrosia purpurea* while the level of ash in *Zornia glochidiata* was the lowest. For Ngamiland samples, ash content was high for *Chamaecrista abscus,* and the lowest was observed for *Crotalaria sphaerocarpa*. These values for ash are higher than for the basal forage *Eleusine coracana* (Madibela & Modiakgotla, 2004), suggesting that legumes would supply more minerals than basal forage and are suitable to supply minerals to ruminants. Fibre components varied with location and with forage type; this was not tested statistically, as the same plants were not growing in the different sites, but distinct trends were observed between Tswapong samples and those obtained from Ngamiland. For example, in samples obtained from Tswapong, neutral detergent fibre (NDF) averaged 404 g/kg, with the highest concentration noted for *Zornia glochidiata*. These values are higher than in samples obtained from Ngamiland, which averaged 327.4 g/kg ash. The NDF levels for samples harvested from Ngamiland were lower for *Indigofera* sp. and higher for both *C. abscus* and *Tephrosia* sp. Ngamiland is recognised for its higher rainfall (≈ 600 mm/year) than eastern Botswana (≈ 420 mm/year) (Bernard et al., 2017; Parida & Moalafhi, 2008), where Tswapong is located. This may be the reason for differences observed, since location influences the availability of soil moisture and hence forage quality. In areas with higher rainfall, plants do not accumulate fibre quickly but maintain a high protein content for relatively longer periods than in areas with low rainfall. Effect of site was, however not tested in this study. The growth stages of these plants were also not studied, and sampling happened once in the middle of the growth season during flowering (Bernard et al., 2017). This is important because as plants mature, concentrations of fibre components increase, influencing the fibre content in forages. The concentrations of NDF observed for samples from Ngamiland are within the values noted for effective rumen activity and animal performance. According to Harris (2003), the beneficial aspects of dietary fibre are due to its effect on regurgitation (cud chewing), chewing, salivation, rumen pH (acidity), and rumen function. However, higher NDF such as that found in *Zornia glochidiata* and *C. rotundifolia* may hinder dry matter intake as a result of restricted rumen fill if the forages are offered as sole feed, which is unlikely since it is anticipated that they will be utilised as supplements. With regard to acid detergent fibre (ADF), samples harvested from Ngamiland had lower ADF concentrations, averaging 160.6 g/kg, with the lowest observed for *Indigofera* sp. Seguin et al. (2002) observed that soil moisture deficit increased ADF levels. Under the circumstances described above, higher ADF is bound to affect digestibility (Harris Jr., 2003) when such plants are fed to ruminants. In contrast, Seguin et al. (2002) found that when ADF is increased while ADL content was reduced, led to increase forage digestibility.

In vitro gas production

Total gas procedure by Menke & Steingass (1988) estimate fermentation processes in the rumen, and the gas measured is regarded as waste from such processes. The measurement gives insight into the extent of the degradability of a feed material and its degradation rate. Gas produced during incubation was higher for *Z. glochidiata* (55 ml/0.5 g) and lower for *T. lupinifolia* (22 ml/0.5 g), while *C. rotundifolia* and *T. purpurea* both produce 35 ml/0.5 g of gas. The interpretation of this result is that *Z. glochidiata* would undergo higher degradation in the rumen of ruminants than *T. lupinifolia*, even though the former has both higher fibre (NDF and ADF) and a higher concentration of condensed tannins than the latter. Condensed tannins have been noted to reduce degradability (Gemeda & Hassen, 2015) by binding to useful substrates in the rumen and denying microorganisms the required nutrients for growth and fermentative processes. This binding of nutrients by CTs may, however, be beneficial if the concentration of condensed tannins is less than 5.0 g/kg, as tannin-bound protein escaping microbial degradation will increase the amount of protein supplied post-ruminally. This increase in protein can be used for productive purposes such as growth, milk production, and immune function. Results of Hassen et al. (2008) showed *in vitro* organic matter digestibility to be moderate for *Indigofera* spp. in

South Africa. A review of literature by Abdullah & Kumalasari (2011) in Indonesia indicated that *Indigofera* spp. have a high protein (27–29%) and mineral (Ca, P, Mg, and Zn) content, a moderate NDF structure, and a high digestibility value for ruminants (67–81%). These values of CP for *Indigofera* spp. are comparable to some accessions tested by Hassen et al. (2008) in South Africa, where they found medium to high levels of CP (15.9%–29.9%). Condensed tannins also reduce the yield of methane gas in the rumen (Gemeda & Hassen 2015; Piñeiro-Vázquez et al., 2015). Alternatively, the high gas production by *Z. glochidiata* regardless of its high fibre content may be due to the disproportional production of methane gas compared to carbon dioxide. Forage with relatively high cell wall content produces high amounts of methane in the rumen. In the current study, methane yield was not estimated, and future studies need to incorporate this important parameter because of its current and future implications in agriculture.

Conclusions

The legumes investigated have high protein and mineral content, making them suitable candidate forages for supplying the nutrients found in low quantities in basal low-quality hay, straw, or crop residues. Different amounts of gas production during *in vitro* incubation were observed, probably as a result of differences in fibre and condensed tannin concentration. Forages with high gas production suggest high fermentation extent or rate and thus high *in vitro* digestibility, and therefore would be expected to supply more nutrients to ruminants. Measurements of methane and digestibility as well as feeding studies are recommended for future experiments to obtain information that would inform strategies on how best to utilise these plants as protein supplements for livestock.

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References

Abdullah, L. & Kumalasari N. R. (2011) Amino acid contents of *Indigofera arrecta* leaves after application of foliar fertilizer. *Journal of Agricultural Science and Technology A,* **1**, 1224–1227

AOAC (1996) Official methods of analysis. Association of Analytical Chemists, Washington, DC, USA.

Bernard, N., Losologolo, M., Batlang, U., Ngwako, S., Mashungwa, G.N., Tselaesele, N.M. & Pule-Meulenberg, F. (2017) Symbiotic performance of grain and wild herbaceous legumes in the Okavango Delta and Tswapong region of Botswana. *Symbiosis*
10.1007/s13199-017-0515-2

Chen, Y., Yan, T., Gao, C., Cao, W. & Huang, R. (2014) Natural products from the genus *Tephrosia*. *Molecules*, **19**, 1432–1458.

Gemeda, B.S. & Hassen, A. (2015) Effect of tannin and species variation on in vitro digestibility, gas, and methane production of tropical browse plants. *Asian-Australasian Journal of Animal Sciences*, **28**, 188–199.

Harris, Jr., B. (2003). The importance of fiber in feeding dairy cattle. Dairy production guide. Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. http://edis.ifas.ufl.edu

Hassen, A., Rethman, N.F. Apostolides, G.Z. & van Niekerk, W.N. (2008) Forage production and potential nutritive value of 24 shrubby *Indigofera* accessions under field conditions in South Africa. *Tropical Grasslands*, **42**, 96–103.

Hoste, H., Martinez-Ortiz-De-Montellano, C., Manolaraki, C.F., Brunet, S., Ojeda-Robertos, N., Fourquaux, I., Torres-Acosta, J.F.J. & Sandoval-Castro, C.A. (2012) Direct and indirect effects of bioactive tannin-rich tropical and temperate legumes against nematode infections. *Veterinary Parasitology*, **186**, 18–27.

Jensen, T.L. (2012) Livestock foraging behavior in response to sequence and interactions among alkaloids, tannins, and saponins. PhD thesis, Utah State University, Logan, UT, USA.

Lamy, E., Rawel, H., Schweigert, F.J., Silva, F.C., Ferreira, A., Costa, A.R., Antunes, C., Almeida, A.M., Coelho, A.V. & Sales-Baptista, E. (2011) The effect of tannins on Mediterranean ruminant ingestive behaviour: the role of the oral cavity. *Molecules,* **16**, 2766–2784.

Madibela, O.R. & Modiakgotla, E. (2004) Chemical composition and in vitro dry matter digestibility of indigenous finger millet (*Eleusine coracana*) in Botswana. *Livestock Research for Rural Development*, **6**, article 26. http://www.lrrd.org/lrrd16/4/madi16026.htm

Makkar, H.S. (2000) Quantification of tannins in tree foliage. A laboratory manual for the FAO/IAEA coordinated research project on use of nuclear and related techniques to develop simple tannin assays for predicting and improving the safety and efficiency of feeding ruminants on tanniferous tree foliage IAEA Working Document. IAEA, Vienna.

Menke, K.H. & Steingass, H. (1988) Estimation of the energetic feed value obtained by chemical analysis and in vitro gas production using rumen fluid. *Animal Resources Development,* **28**, 7–55.

Naumann, H.D., Armstrong, S.A., Lambert, B.D., Muir, J.P., Tedeschi, L.O. & Kothmann, M.M. (2014) Effect of molecular weight and concentration of legume condensed tannins on *in vitro* larval migration inhibition of *Haemonchus contortus*. *Veterinary Parasitology*, **199**, 93–98.

Obopile, M., Karabo, O., Pearl Tshipinare, B., Losologolo, M., Bernard, N., Ngwako, S., Batlang, U., Nnaniki Mashungwa, G., Tselaesele, N. & Pule-Meulenberg, F. (2018) Increasing yields of cereals: benefits derived from intercropping with legumes and from the associated bacteria. This volume.

Parida, B.P. & Moalafhi, D.B. (2008) Regional rainfall frequency analysis for Botswana using L-Moments and radial basis function network. *Physics and Chemistry of the Earth,* **33**, 614–620.

Piñeiro-Vázquez, A.T., Canul-Solís, J.R., Alayón-Gamboa, J.A., Chay-Canul, A.J., Ayala-Burgos, A.J., Aguilar-Pérez, C.F., Solorio-Sánchez, F.J. & Ku-Vera, J.C. (2015) Potential of condensed tannins for the reduction of emissions of enteric methane and their effect on ruminant productivity. *Archivos de Medicina Veterinaria,* **47**, 263–272.

Seguin, P., Mustafa, A.F. & Sheaffer, C.C. (2002) Effects of soil moisture deficit on forage quality, digestibility, and protein fractionation of Kura clover. *Journal of Agronomy and Crop Science*, **188**, 260–266.

Silanikove, N., Pevevolotsky, A. & Provenza, F.D. (2001) Use of tannin-binding chemical to assay for tannins and their negative postingestive effects in ruminants. *Animal Feed Science and Technology*, **91**, 69–81.

Stolter, C. (2018) What is quality for a ruminant? A short introduction to the meaning of plant chemical composition measurements. This volume.

Stolter, C., Ramoelo, A., Kesch, K., Madibela, O., Cho, M.A. & Joubert, D. (2018) Forage quality and availability for large herbivores. This volume.

Tarawali, S.A. (1995) Evaluation of *Chamaecrista rotundifolia* accessions as a fodder resource in subhumid Nigeria. *Tropical Grasslands,* **29**, 129–133.

Tedeschi, L.O., Ramirez-Restrepo, C.A. & Muir, J.P. (2014) Developing a conceptual model of possible benefits of condensed tannins for ruminant production. *Animal*, **8**, 1095–1105.

Villalba, J.J. & Landau, S.Y. (2012) Host behaviour, environment and ability to self-medicate. *Small Ruminant Research,* **103**, 50–59.

Waghorn, G.C., Ulyatt, M.J., John, A. & Fisher, M.T. (1987) The effect of condensed tannins on the site of digestion of amino acids and other nutrients in sheep fed on *Lotus corniculatus* L. *British Journal of Nutrition*, **57**, 115–126.

Wilson, R.A. (2009) Fit for purpose — the right animal in the right place. *Tropical Animal Health and Production*, **41**, 1081–1090.

References [CrossRef]

Abdullah, L. & Kumalasari N. R. (2011) Amino acid contents of *Indigofera arrecta* leaves after application of foliar fertilizer. *Journal of Agricultural Science and Technology A*, **1**, 1224–1227

AOAC (1996) Official methods of analysis. Association of Analytical Chemists, Washington, DC, USA.

Bernard, N., Losologolo, M., Batlang, U., Ngwako, S., Mashungwa, G.N., Tselaesele, N.M. & Pule-Meulenberg, F. (2017) Symbiotic performance of grain and wild herbaceous legumes in the Okavango Delta and Tswapong region of Botswana. *Symbiosis*. CrossRef

Chen, Y., Yan, T., Gao, C., Cao, W. & Huang, R. (2014) Natural products from the genus *Tephrosia*. *Molecules*, **19**, 1432–1458. CrossRef

Gemeda, B.S. & Hassen, A. (2015) Effect of tannin and species variation on in vitro digestibility, gas, and methane production of tropical browse plants. *Asian-Australasian Journal of Animal Sciences*, **28**, 188–199. CrossRef

Harris, Jr., B. (2003). The importance of fiber in feeding dairy cattle. Dairy production guide. Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. http://edis.ifas.ufl.edu

Hassen, A., Rethman, N.F. Apostolides, G.Z. & van Niekerk, W.N. (2008) Forage production and potential nutritive value of 24 shrubby *Indigofera* accessions under field conditions in South Africa. *Tropical Grasslands*, **42**, 96–103.

Hoste, H., Martinez-Ortiz-De-Montellano, C., Manolaraki, C.F., Brunet, S., Ojeda-Robertos, N., Fourquaux, I., Torres-Acosta, J.F.J. & Sandoval-Castro, C.A. (2012) Direct and indirect effects of bioactive tannin-rich tropical and temperate legumes against nematode infections. *Veterinary Parasitology*, **186**, 18–27. CrossRef

Jensen, T.L. (2012) Livestock foraging behavior in response to sequence and interactions among alkaloids, tannins, and saponins. PhD thesis, Utah State University, Logan, UT, USA.

Lamy, E., Rawel, H., Schweigert, F.J., Silva, F.C., Ferreira, A., Costa, A.R., Antunes, C., Almeida, A.M., Coelho, A.V. & Sales-Baptista, E. (2011) The effect of tannins on Mediterranean ruminant ingestive behaviour: the role of the oral cavity. *Molecules*, **16**, 2766–2784. CrossRef

Madibela, O.R. & Modiakgotla, E. (2004) Chemical composition and in vitro dry matter digestibility of indigenous finger millet (*Eleusine coracana*) in Botswana. *Livestock Research for Rural Development*, **6**, article 26. http://www.lrrd.org/lrrd16/4/madi16026.htm

Makkar, H.S. (2000) Quantification of tannins in tree foliage. A laboratory manual for the FAO/IAEA coordinated research project on use of nuclear and related techniques to develop simple tannin assays for predicting and improving the safety and efficiency of feeding ruminants on tanniferous tree foliage IAEA Working Document. IAEA, Vienna.

Menke, K.H. & Steingass, H. (1988) Estimation of the energetic feed value obtained by chemical analysis and in vitro gas production using rumen fluid. *Animal Resources Development*, **28**, 7–55.

Naumann, H.D., Armstrong, S.A., Lambert, B.D., Muir, J.P., Tedeschi, L.O. & Kothmann, M.M. (2014) Effect of molecular weight and concentration of legume condensed tannins on *in vitro* larval migration inhibition of *Haemonchus contortus*. *Veterinary Parasitology*, **199**, 93–98. CrossRef

Obopile, M., Karabo, O., Pearl Tshipinare, B., Losologolo, M., Bernard, N., Ngwako, S., Batlang, U., Nnaniki Mashungwa, G., Tselaesele, N., Pule-Meulenberg, F. (2018) Increasing yields of cereals: benefits derived from intercropping with legumes and from the associated bacteria. This volume. CrossRef

Parida, B.P. & Moalafhi, D.B. (2008) Regional rainfall frequency analysis for Botswana using L-Moments and radial basis function network. *Physics and Chemistry of the Earth*, **33**, 614–620. CrossRef

Piñeiro-Vázquez, A.T., Canul-Solís, J.R., Alayón-Gamboa, J.A., Chay-Canul, A.J., Ayala-Burgos, A.J., Aguilar-Pérez, C.F., Solorio-Sánchez, F.J. & Ku-Vera, J.C. (2015) Potential of condensed tannins for the reduction of emissions of enteric methane and their effect on ruminant productivity. *Archivos de Medicina Veterinaria*, **47**, 263–272. CrossRef

Seguin, P., Mustafa, A.F. & Sheaffer, C.C. (2002) Effects of soil moisture deficit on forage quality, digestibility, and protein fractionation of Kura clover. *Journal of Agronomy and Crop Science*, **188**, 260–266. CrossRef

Silanikove, N., Pevevolotsky, A. & Provenza, F.D. (2001) Use of tannin-binding chemical to assay for tannins and their negative postingestive effects in ruminants. *Animal Feed Science and Technology*, **91**, 69–81. CrossRef

Stolter, C. (2018) What is quality for a ruminant? A short introduction to the meaning of plant chemical composition measurements. This volume. CrossRef

Stolter, C., Ramoelo, A., Kesch, K., Madibela, O., Cho, M.A. & Joubert, D. (2018) Forage quality and availability for large herbivores. This volume. CrossRef

Tarawali, S.A. (1995) Evaluation of *Chamaecrista rotundifolia* accessions as a fodder resource in subhumid Nigeria. *Tropical Grasslands*, **29**, 129–133.

Tedeschi, L.O., Ramirez-Restrepo, C.A. & Muir, J.P. (2014) Developing a conceptual model of possible benefits of condensed tannins for ruminant production. *Animal*, **8**, 1095–1105. CrossRef

Villalba, J.J. & Landau, S.Y. (2012) Host behaviour, environment and ability to self-medicate. *Small Ruminant Research*, **103**, 50–59. CrossRef

Waghorn, G.C., Ulyatt, M.J., John, A. & Fisher, M.T. (1987) The effect of condensed tannins on the site of digestion of amino acids and other nutrients in sheep fed on *Lotus corniculatus* L. *British Journal of Nutrition*, **57**, 115–126. CrossRef

Wilson, R.A. (2009) Fit for purpose — the right animal in the right place. *Tropical Animal Health and Production*, **41**, 1081–1090. CrossRef

Impacts of fire history in a semi-arid woodland savanna

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Rangelands

Abstract: Fire is known to be an important element shaping semi-arid ecosystems. Within SASSCAL we conducted several projects in the woodland savanna of the Waterberg Plateau Park to gain a better understanding of the impact of fire on ecosystem properties and processes (soil characteristics, species composition and structure of the vegetation, changes in plant forage quality, insect biodiversity, and the utilization of habitat and plants by large herbivores). Four adjacent areas of around 2,000 ha–2,500 ha each with different times since last burn were studied (in 2014, when most of the measurements were done, the areas had been burnt 2, 3, 14, and 24 years prior to the study). We found inconsistent effects of different fire histories on soil nutrients, soil organic carbon, and soil respiration, which suggests that soil resources return rapidly (within a year or two) to pre-fire conditions at our sites. We also assume (based on the standing biomass of the four areas during the study) that the fires were likely to have not been sufficiently intense to cause long-term detrimental impacts and impair the recovery of soil resources at our sites. Furthermore, fire positively affected the grass component by increasing grass density and enhancing productivity. Fire maintained open savannas through the top-kill of woody plants but did not alter plant species composition. The influence of burning on the quality of grasses was relatively short-lived (two years after burning, grass quality in burnt sites was comparable with that of unburnt sites). However, trees, whose leaves are generally higher in protein, remained at a higher quality for longer periods after fire and thus served as supplementary food not only for browsers and mixed feeders but also for herbivores generally considered to be 'pure' grazers (e.g., red hartebeest, buffalo). Fire had a negative impact on small ground-nesting bees, whereas bigger and above-ground-nesting bees seemed to be favoured by fire. Ground-dwelling invertebrate communities differed with time since last burn, the main driver of the differences being litter cover. Our findings in relation to fire illustrate that heterogeneous habitats, as a result of pyrodiversity, are of great benefit for the habitat utilization and plant utilization of large herbivores as well as increasing the overall diversity of invertebrates. Managers can maximise biodiversity and diversity in resource and habitat utilization by maximising the diversity of fire histories in the managed areas (commonly termed patch-mosaic burning).

Resumo: O fogo é conhecido por ser um importante factor na modelação dos ecossistemas semi-áridos. No contexto do SASSCAL, realizámos vários projectos na savana arborizada do Parque Nacional de Waterberg, de modo a obter uma melhor compreensão do impacto do fogo nas propriedades e processos do ecossistema (características do solo, composição e estrutura da vegetação, alterações na qualidade de forragem, biodiversidade de insectos e utilização do habitat e das plantas pelos grandes herbívoros). Foram estudadas quatro áreas adjacentes, de cerca de 2000 a 2500 ha, com diferentes tempos desde o último incêndio (em 2014, altura em que a maioria das medições foi realizada, as áreas haviam sido queimados há 2, 3, 14 e 24 anos). Encontrámos efeitos inconsistentes de diferentes historiais de fogo nos nutrientes, carbono orgânico e respiração do solo, o que sugere que os recursos pedológicos retornam rapidamente (dentro de um ano ou dois) a condições de pré-fogo

nos nossos locais. Assumimos também (com base na biomassa existente nas quatro áreas durante o estudo) que os fogos não deverão ter sido suficientemente intensos para causar impactos negativos de longa duração e comprometer a recuperação dos recursos pedológicos nos nossos locais. Além disso, o fogo afectou positivamente as gramíneas ao aumentar a densidade de ervas e intensificou a produtividade. O fogo manteve as savanas abertas através da morte de plantas lenhosas, mas não alterou a composição específica de plantas. A influência da queima na qualidade de gramíneas foi relativamente breve (dois anos após o incêndio, a qualidade das gramíneas era comparável à dos locais não queimados). No entanto, as árvores cujas folhas têm geralmente um maior conteúdo de proteína permaneceram com maior qualidade por períodos maiores após o fogo e, assim, serviram como alimento suplementar a *browsers* e animais de dieta mista, mas também a herbívoros geralmente considerados como herbívoros "puros" (e.x.: caama; bufalo). O fogo teve um impacto negativo em pequenas abelhas que nidificam no solo, enquanto que abelhas maiores que nidificam acima do solo pareceram ser favorecidas pelo fogo. Comunidades de invertebrados no solo variaram com o tempo desde o último incêndio, sendo o principal factor das diferenças a cobertura de detritos. As nossas descobertas em relação ao fogo ilustram que habitats heterogéneos, como resultado da pirodiversidade, são de grande benefício para a utilização do habitat e das plantas pelos grandes herbívoros, e aumentam também a diversidade geral de invertebrados. Os gestores podem maximizar a biodiversidade e diversidade da utilização dos recursos e do habitat ao maximixar a variedade de historiais de fogos em áreas geridas (comumente denominadas de *patch-mosaic burning*).

General introduction

It is well known that fires shape ecosystems, but our understanding of the directions and extent of this shaping as well as the interactions between fires and other ecosystem components is limited. In African savannas, fire management approaches have changed from attempts to completely exclude fire, to rigid fire regimes with little variability, to flexible fire regimes based on utility (woody biomass; woody mortality; grass quantity and quality; soil fertility; and less commonly biodiversity) (van Wilgen, 2009). The current paradigm is to manage fire for heterogeneity and biodiversity (van Wilgen, 2009). Despite the purported objective of parks to conserve biodiversity, that goal is often not practically considered much by park managers, particularly in Namibian parks, where finances and knowledge transfer are extremely limited. Here we investigated the effects of fire on soil properties, vegetation species composition and structure, plant quality, biodiversity of insects, and habitat and plant utilization by large herbivores. Each component of the study is outlined below, followed by a synthesis and management conclusion.

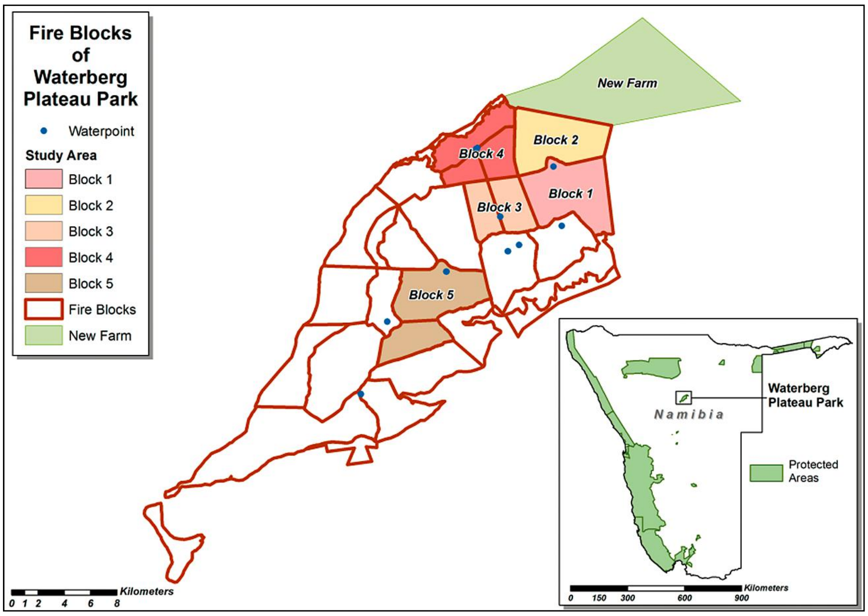


Figure 1: The location of Waterberg Plateau Park in Namibia, and the location of the different fire blocks 1-4 (used for this study), as well as the study area used to investigate frost effects, 5. "New farm" is a portion purchased from a neighbouring farmer that is being incorporated into the park.

The Waterberg Plateau Park (WPP) — our study area

The WPP is a relatively small park of about 47,000 ha in central Namibia, about 280 km northeast of Windhoek and about 60 km east of Otjiwarongo (Fig. 1). The primary aim of the park since its proclamation in 1972 has been to breed up rare, high-value species of antelope and other herbivores. The sandstone plateau rises up to 300 m above the surrounding plain and is on average between 1,550 m and 1,850 m above sea level (Mukaru, 2009). It extends about 50 km in length and 16 km in width. The park lies on aeolian dystrophic Kalahari sands from the Kalahari basin (Erb, 1993), which are heavily leached (Mukaru, 2009). The plateau experiences warm summers with temperatures reaching up to 40 ^{0}C in the hottest months, while winter temperatures can drop to below –10 ^{0}C (www.sasscal-weathernet.org). The mean annual rainfall recorded for the period 1981 to 2001 was 425.5 mm ± 129 mm, with February being the wettest month (Erckie, 2007). The vegetation of the WPP is dominated by typical broadleaf woodland savanna species such as *Terminalia sericea*,

Table 1: Different treatments (blocks) with their mean fire return intervals since 1976 and time since last burn (at 2016) based on interviews with rangers. The last fire was in September 2013, in block 1. Time since last burn depends on the year (2014–2016) when the measurements were taken.

Treatment (block)	Mean fire return interval (years)	Time since last burn (years) – at 2016	Year of last burn
1	6.2	3	2013
2	9.3	4	2012
3	9.3	16	2000
4	18.5	26	1990

Burkea africana, *Ochna pulchra*, *Combretum collinum*, *Combretum psidioides*, *Grewia flavescens,* and *Bauhinia petersiana* as well as *Acacia ataxacantha* and *Acacia fleckii.* Species such as *Pterocarpus angolensis* and *Baikea plurijuga* are absent as a result of the low rainfall and very cold temperatures occasionally experienced in winter. Grass species include *Eragrostis pallens*, *Eragrostis jeffreysii*, *Brachiaria nigropedata*, *Digitaria seriata*, *Panicum kalaharense, Stipagrostis uniplumis, and Aristida stipitata* (Erb, 1993; Schneider, 1993).

We investigated the impacts of time since last burn in the WPP, where fire blocks are generally clearly delineated, with access roads acting as effective fire breaks. The fire history was obtained through interviews with longtime staff members. The study site is located on the northern part of the Park Plateau at the more arid end of Namibia's woodland savanna vegetation type (Giess, 1971).

In the late 1950s the plateau was run as cattle rangeland. The farm owners burned every four years during dry cycles and every three to four years during wet cycles (Jankowitz, 1983). It is perceived that woody vegetation cover has increased in the park since its proclamation and the termination of the regular burning programme by farmers. The reduction in anthropogenic fires and consequent increase in the cover of woody species, such as *T. sericea*, is thought to have caused a reduction in the density of palatable climax perennial grass species such as *B. nigropedata* and *D. seriata*. No vegetation monitoring programmes existed in the WPP prior to our study, and thus the perceived changes have not been tested.

General common methods

The park is divided into six fire zones, which are further subdivided into fire blocks, with roads acting as fire breaks. Each block has a different history (fire frequency, time since last burn [TSLB], year of fire). The studies were done in four fire blocks (treatments) adjacent to one another (Fig. 1.) with different fire histories (Tab. 1). Treatment 1: treatments 2, 3, and 4: burned in 2013, 2012, 2000, and 1990, respectively. A space-for-time substitution approach was applied (Pickett, 1989).

Most of the studies were conducted along randomly located 200 m transects within each block at 40 m (in some cases 20 m) intervals along the transects. This allowed comparisons to be made amongst different parameters within each block (Fig. 2a–d).

A. The impacts of fire history on soils

Introduction

Why is it important? Fire is recognized as an integral part of savanna ecosystems that has shaped those landscapes since the Miocene and continues to do so. The prevalence of fire in this system influences nutrient cycling and soil carbon (C) pools (Holt & Coventry, 1990). Fire may affect ecosystem productivity and biogeochemical processes through nutrient volatilization, altered organic matter quantity, and, indirectly, altered vegetation structure (Satyam & Jayakumar, 2012). Despite the resulting general effects on soil resources, substantial uncertainty about fire history effects exists (Concilio et al., 2006), especially in semi-arid ecosystems. Semi-arid ecosystems are typically much more heterogeneous than mesic systems, with large biotic and abiotic differences among distinct vegetation patch types such as shrubs, grass, and bare ground (de Graaff et al., 2014). Changes in biogeochemical cycles and microbial physiological responses vary among vegetation patch types (Han et al., 2014). We wanted to know whether different fire frequencies in the park had any negative effects on soil properties. We specifically investigated the effects of time since last burn on these properties. Because fire also affects vegetation structure, and thus could indirectly affect soil in this way (Coetsee et al., 2010; Holdo et al., 2012; Khavhagali, 2008), we were also interested in the effects of vegetation patch types (under shrub, under grass, and bare ground) on these parameters. We explored the independent and interactive effects of time since last burn and patch type on soil nutrients, soil organic carbon (SOC), and soil respiration in this semi-arid ecosystem.

Methods

To determine the independent and interactive effects of fire history and vegetation patch types on soil nutrients and SOC, we collected soil samples in four fire blocks with different fire histories (time since last burn ranging from 1 to 25 years and fire intervals ranging from 6.2 to 18.5 years). In each fire block, six transects (200 m) were laid out randomly, and five soil samples were collected at every 40 m along each transect in the 0–10 cm soil layer, amounting to 30 samples per treatment. Chemical analyses for soil nutrients (total N, P, K, Na, Ca, Mg) and SOC were performed at the soil laboratory of the Ministry of Agriculture, Water and Forestry. To determine the effect of fire history on soil respiration and how it responds under different vegetation patch types, we used a LI-6400XT instrument. Eight sampling sites were established in all four fire blocks, with three treatments per site. The treatments represented the vegetation patch types (bare ground, under grass, and under shrub). Additionally, we collected soil cores from each sampling point for the

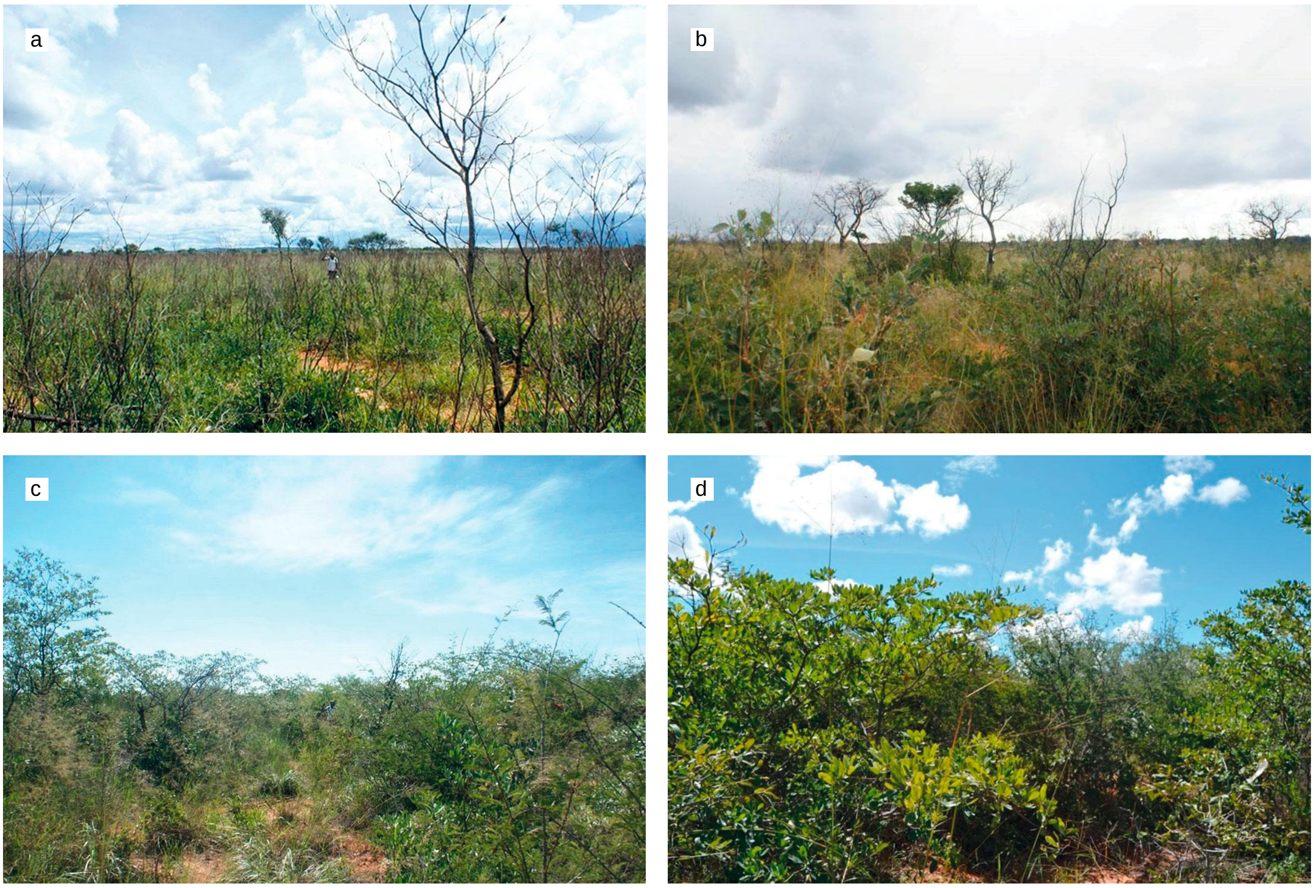


Figure 2: Vegetation structure in (a) Block 1, burned in September 2013, (b) Block 2, burned in 2012, (c) Block 3, last burned in 2000, (d) Block 4, last burned in in 1990.

assessment of gravimetric water content and a laboratory incubation experiment that allowed us to measure potential carbon mineralization under controlled conditions. In the incubation experiment, soil cores were incubated for 3 weeks at 60% water holding capacity, at room temperature. Soil CO_2 efflux was measured for 15 days with an infrared gas analyzer (Licor 6400).

Results

SOC was not significantly different among fire blocks and vegetation patch types. The blocks that burned 2 and 24 years ago (in 2012 and 1990, blocks 2 and 4) had low total N relative to the blocks that burned in 2013 and 2000 (blocks 1 and 3). Block 2, which burned 2 years ago, had the lowest available P relative to other fire blocks. Sodium showed a consistent trend, decreasing with increasing time since last burn. There was no clear trend for other exchangeable cations K, Mg, and Ca; however, their levels were high in the recently burned area (block 1). These cations typically increase after fire because of their presence in the ash as a result of the high threshold temperatures at which these elements volatilize (Satyam & Jayakumar, 2012). These high temperatures might have not been reached during the fire. Soil respiration responded to time since last burn differently under different vegetation patch types, with the under-shrub treatment generally having higher soil CO_2 efflux relative to the under-grass and bare-ground treatments. This suggests that fire may have important indirect effects on soil respiration through its alteration of vegetation cover. In the laboratory experiment, soil CO_2 efflux was higher relative to the field experiment and was not significantly different among vegetation patch types. Based on the field and incubation results, this study concluded that the higher soil respiration observed under shrubs in the field experiment is largely attributable to root respiration, suggesting that fire did not significantly impact soil microbes.

Synthesis and outlook

What can we learn from it? Fire history had a limited and inconsistent effect on soil nutrients, SOC, and soil respiration. This suggests that soil resources return rapidly to pre-fire conditions. In addition, these fires were likely to have not been sufficiently intense to cause long-term detrimental impacts and impair the recovery of soil resources (the standing fuel biomass measurements suggest that fires are generally not very intense). Moreover, site-to-site spatial variation (tree cover, grass cover, microtopography) may have had a stronger controlling influence on soil nutrients, SOC, and soil respiration. Therefore, there should be no concern about using fire within the experienced frequencies (6.2–18.5 years) as a tool to improve positive resource utilization.

B. The impacts of fire history on vegetation

Introduction

Why is it important? Vegetation-fire research is a well-established field in African savannas. Nevertheless, Namibian vegetation-fire studies are very limited, even as fire regimes are being altered in different ways without follow-up research and monitoring. Considering that most of Namibia is arid to semi-arid, Joubert et al. (2012) predicted that fire, although not frequent and generally cooler (low fuel loads) than in wetter savannas, is necessary for keeping savannas in an open grassy state when they occur at the time of seedling establishment. At WPP, the impact of fire history on vegetation structure and species composition was studied in the same fire blocks introduced above.

Methods

At every sample point along the transects, the following three techniques were used: the modified point-centred quarter method (Cottam & Curtis, 1956; Trollope et al., 2013) to determine density and structure, the Bitterlich gauge (Friedel & Chewings, 1988; Zimmermann & Mwazi, 2002) to determine woody cover at different heights, and the visual obstruction reading (VOR) method to estimate standing grass biomass.

The point-centred quarter method used is a version of the Cottam & Curtis (1956) method adapted by Trollope et al. (2013). In each quarter within a 20 m radius (Trollope et al., 2013), the distances to the nearest live perennial grass and to woody species of < 1 m, 1–2 m, 2–3 m, 3–4 m, and > 4 m were measured and recorded (Figure 3). The basal diameter of the perennial grasses and the height of the woody plants in the different height classes were also measured. The different species being measured were also identified and recorded.

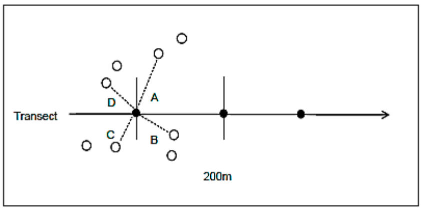


Figure 3: Illustration of how the point-centred quarter method works (Adapted from Mitchell, 2007).

The Bitterlich gauge was used to estimate woody canopy cover (Friedel & Chewings, 1988; Zimmermann & Mwazi, 2002). Zimmermann & Mwazi (2002) found it to be an accurate method to estimate woody cover. The tip of the longer rod is held below the eye, with the cross-piece and pins held horizontally in the direction of a woody canopy. If the woody canopy extends beyond the two tips (Figure 4a), the canopy is counted and recorded as 1 (converted to a percentage by multiplying with the percentage factor of 5) and its species identified; if the two tips extend beyond the canopy, then it is ignored (Figure 4b). This procedure was repeated until a 360^0 turn clockwise had been made at every PCQ point along each transect.

The VOR method was used to estimate standing grass biomass (Robel, et al., 1970; Uresk et al., 2009). This method requires little effort to monitor rangelands and was tested by Joubert et al. (2015) in Namibia, including in the study area, and found moderate to high levels of correlation of grass biomass and VOR. This method requires two people. At each point along the transects, one person stands with a 2 m pole on the soil surface subdivided into 2.5 cm rings with alternating red and white bands. The second person looks towards pole A from pole B with his eye at the 1 m mark. The distance between the poles is 4 m. The lowest visible band obscured by grasses is determined and the number of bands obstructed by grasses counted and recorded. This is repeated so that four VORs are recorded at each designated point (one from each cardinal direction). The readings were calibrated with actual biomass readings from 60 points in the study area. A regression equation between the VOR and dry weight (g) of the grasses was derived to convert all VORs to biomass.

Results

The findings from the study showed that fire in this semi-arid woodland savanna stimulates the regrowth and recruitment of new grass shoots by increasing the grass density and grass biomass in the recently burned areas, without significant changes in grass species composition. Without long periods of fire, perennial grasses accumulate moribund material, which becomes potential fuel load should a fire occur. While fire did not significantly reduce woody density, it caused significant top-kill of woody individuals, reducing the woody cover and thereby maintaining an open savanna. Consequently, in the absence of fire, woody plants grow larger and their individual canopy areas become bigger, resulting in a higher woody cover, and thus a more closed savanna. Woody species composition was not influenced by time since last burn, indicating that there was no plant

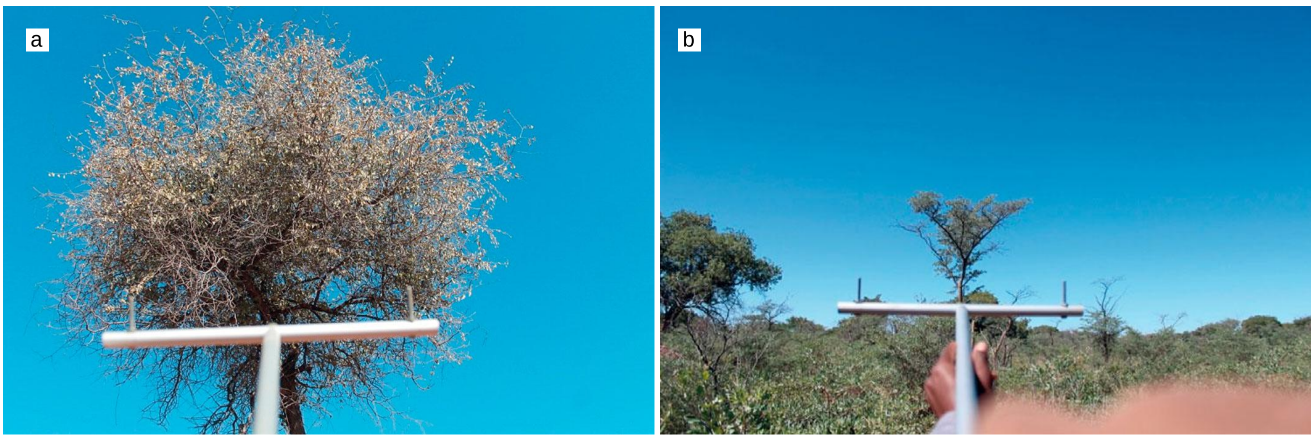


Figure 4: The use of the Bitterlich gauge (a) pointed at a woody canopy to estimate woody cover. In this instance, the overlap of the tree canopy past the pins means this is recorded as cover and (b) pointed at a woody canopy to estimate woody cover. In this instance, there is no overlap and thus this is not recorded as cover (Images: D.F Joubert, J.A.N Kandjai).

species succession occurring in the current time frame, but differences in structure were clearly evident.

Synthesis and Outlook

What can we learn from it? Fire positively affected the grass component by increasing grass density and enhancing productivity through the removal of moribund material and plant cover, but grass biomass was significantly reduced in the first season after fire (recovering a year later). Fire maintains open savannas by causing top-kill of woody plants and not causing total mortality, which is evident as species composition is not altered. Based on these findings, it appears that a modest increase in fire frequency and the burning of areas that have not been burnt in a long time (14–24 years) will have no negative impacts on plant species composition but will only change the structure. Such fires would need to be set after high rainfall seasons to significantly cause top-kill of woody plants (and thus open up closed woodland sites) and improve the grass quantity and quality.

C. Impacts of fire history on the species composition, abundance, species richness, and diversity of ground-dwelling arthropods

Introduction

Why is it important? Fire has been used as a management tool for centuries (Osborne, 2008). Fire effects have been studied in fire-prone ecosystems worldwide, with much focus on vegetation (Joubert et al., 2012), but less effort has been made to understand the response of arthropods to fire (Davies et al., 2010), and thus the response of arthropods (particularly ground-dwelling ones) to fire remains unclear (Hanula & Wade, 2003).

Methods

The study was done along the same transects that were used for soil, vegetation, and resource utilization sampling. At each sampling point, pitfall traps were exposed for 48 hours in April 2016. Data were collected at 40 m intervals along each transect. Each transect had five pitfall traps, and each fire block had 30 pitfall traps. Invertebrates were identified to morphospecies. A morphospecies is defined by its appearance (Work et al., 2002) rather than its taxonomic relations. Morphospecies can be successfully and efficiently used as surrogates for taxonomic species (Oliver & Beattie, 1996). One-way ANOVA was used to test for significant differences in abundance and diversity (Shannon diversity index and species richness) among the different fire treatments. Nonmetric multidimensional scaling (NMDS) ordination techniques in PC-ORD 6 (McCune & Mefford, 2011) were used to determine which variables drove community composition, and whether the communities differed.

Results

The survey collected 1,755 individuals, which represented 99 morphospecies and 13 taxonomic orders. Of this total, 96% were insects, 3% arachnids, and 1% myriapods. The study found inconsistent differences unrelated to time since last burn. There was a statistically significant difference in abundance but no statistically significant difference in diversity between treatments. NMDS revealed that litter, grass density, and woody cover were the strongest variables driving community composition. Litter was the most important variable in the treatments that burned 16 and 26 years ago (in 2000 and 1990; blocks 3 and 4). There was clear separation of the treatments burnt over a decade ago and the treatments burnt recently, with low levels of overlap suggesting that a diversity of fire regimes at WPP increases the beta diversity of ground-dwelling arthropod species. The findings of this study suggest that time since last burn had little effect on ground-dwelling arthropod abundance and species richness and inconsistent effects on Shannon diversity. Variables other than fire (secondary effects such as litter, grass density, and woody cover) seem to be driving the effects.

Synthesis and Outlook

What can we learn from it? As with other taxa and fire effects, resource managers should not be fixated on implementing the 'correct' fire regime. This will reduce beta and gamma diversity. Resource managers can maximise arthropod diversity by maximising the diversity of fire histories in the managed areas. In the study area, this has been achieved unintentionally through a combination of intended fires, natural fires, and accidental fires.

D. Impacts of fire history on bee abundance and species richness

Introduction

Why is it important? Animal pollination is obligatory for the sexual reproduction of roughly 90% of the world's plant species (Potts et al., 2010). Amongst these animal pollinators, bees are assumed to be the most important pollinator in most ecosystems (Michener, 2007). Beside the well-known honeybees, there are numerous species of wild bees (an estimated 20,000 species worldwide), many of them still unknown and undescribed. There is a need for wild pollinator research, especially in certain areas such as sub-Saharan Africa and other parts of the Southern Hemisphere (Potts et al., 2010). The main objective in this study is to investigate how different burning histories influence wild bee diversity at the study sites. Our study is the first to examine wild bee diversity in the Waterberg in Namibia. The results could help us understand what impact the common practice of burning farmlands has on the survival and diversity of wild bees. With this knowledge, the maintenance of pollinator diversity and the associated ecosystem services on private and communal land may be managed and maintained or even improved.

Methods

Pan traps were placed on the same transects outlined in the previous studies to determine bee diversity and abundance. Pan traps are commonly used in pollinator studies (Campbell & Hanula, 2007). The pan traps consisted of plastic bowls that had been sprayed with UV colour in white, blue, and yellow to attract foraging insects. The pan traps were installed

Figure 5: Pan traps fixed to the woody vegetation in block (4) burned in 1990.

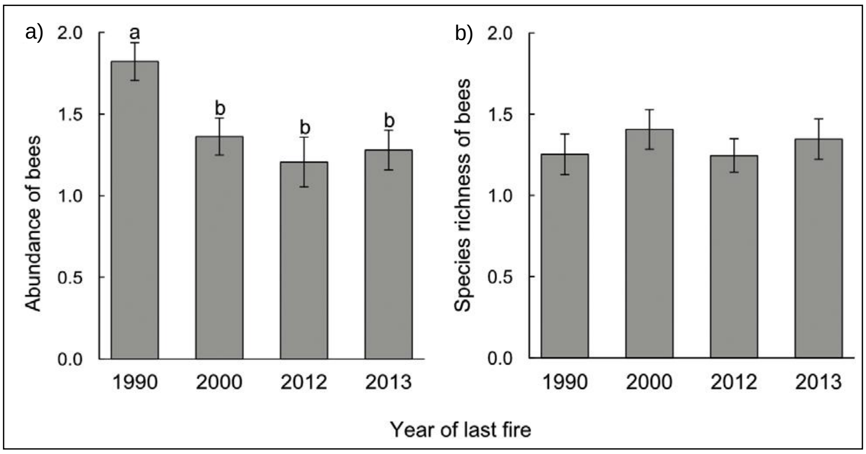


Figure 6: (a) Abundance and (b) species richness of wild bees under the influence of four different burning regimes. The graph is based on model values on the logarithmic scale; whiskers show the standard error of the mean. Different letters indicate significant differences after Tukey HSD *posthoc* comparison (glmer.nb: $F_{4/707}$=19.10, p = <0.001).

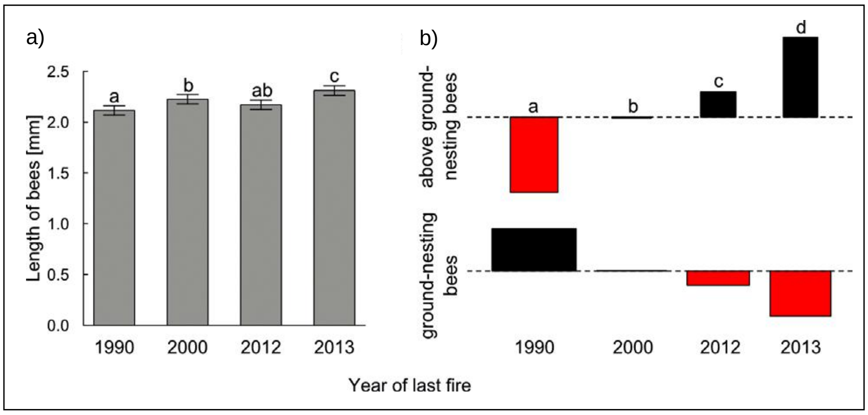


Figure 7: Abundance of bees on the different plot in relation to (a) their body length (in mm) and (b) their nesting-behaviour; (a) The bars show the model estimates for body size after Tukey HSD post-hoc test of the general linear fixed effect model with negative binomial distribution (glmer.nb). Error bars are Standard mean errors (SEM), glm: $F_{3/708}$=8.66, p<0.001; b) the association plot is based on a Chi-square test. If the observed frequency of a cell is greater than the expected one, the box rises above the baseline and is shaded black; otherwise, the box falls below the baseline and is shaded in red. Different letters above the bars show significantly different results.

in vegetation at breast height (Fig. 5) and filled up with water; surface tension was reduced by adding a drop of detergent (Westphal et al., 2008). The pan traps were exposed for 24 hours, repeated four times in October and November 2015 during the onset of the rainy season. Two sets of pan traps, each consisting of three bowls in blue, yellow, and white, were installed 100 m apart, starting from the end line of the transect (between 750 m and 500 m from access roads). After 24 hours the caught insects were collected and preserved with ethanol (Eardley et al., 2010). The collected insects were sorted at a later stage. The collected bees were identified to species level, and morphospecies level where identification to species level was not possible because of gaps in the taxonomic literature. All statistical analyses were calculated using R version 3.2.5 (R Core Team, 2017), except NMDS analyses, which were conducted using PAST software (Hammer et al., 2001).

Results

A total of 3,113 bees were captured in the pan traps. The 3,113 individuals were composed of an estimated 17 different species or morphospecies. Three *Lasioglossum* spp. (65%), *Apis mellifera* (23%) and *Zebramegilla langi* (7%) were the most abundant species. The time since last burn had a significant influence on the overall abundance of bees. Bee abundance was highest on the plot with the oldest vegetation (burnt in 1990) but did not differ between the other fire treatments (Fig. 6a). Total species richness of wild bees was not affected by the time of last burning (Fig. 6b). The nonmetric multidimensional scaling (NMDS) analyses revealed a significant difference between the species composition in the plot that burned in 1990 (block 4), compared to the one that burned most recently (block 1).

The species traits analysis shows that fire seems to be a main driver of bee species composition within the different plots. While ground-nesting bees with a small body size were most abundant on the plot with the oldest vegetation (Fig. 7a), bigger and above-ground-nesting bees were more abundant in recently burned plots (Fig. 7b).

Rangelands

Synthesis and outlook

What can we learn from it? Fire seems to have a negative impact on small ground-nesting bees, which are limited in their dispersal ability because of their small body size. Body size is in most cases linked to the flying ability of bees (Greenleaf et al., 2007). Their nests, which are located not too deep in the ground, appear to be destroyed by fires, which would be in line with findings from a study by Van Nuland et al. (2013) conducted in a savanna biome in Israel. We can conclude, then, that ground-nesting bees with a small body size seem to be mostly restricted to undisturbed areas, while bigger and above-ground-nesting bees seem to prefer foraging on recently burned plots, which may harbor more food resources. This has implications for fire management. Our findings suggest that a patchy burning regime will allow for a highly diverse bee community in a given location. This in turn ensures pollination services to the plant community.

E. The impacts of fire on habitat utilization of large herbivores and changes in their food quality in respect to fire

Introduction

Why is it important? Large herbivores have an enormous impact on ecosystems mainly through their food selection, altering not only the plant community structure but also the chemical composition of plants (e.g., Archibald et al., 2005; McNaughton et al., 1988; Olff & Ritchie, 1998; Stolter, 2008). Different herbivorous feeding strategies have evolved, resulting in differences in food selection and hence in changes in vegetation composition. They also influence fire regimes and, indirectly through their other effects, faunal species composition and diversity.

Fire is another important driver of changes of plant community structure and nutrient composition (e.g., Anderson et al., 2007; Higgins et al., 2007; Roques et al., 2001), which subsequently will affect herbivores and their feeding decisions. Fire is frequently used as a management tool, such as to provide fresh food to herbivores or manage bush encroachment (Anderson et al., 2007; Joubert et al., 2012). Because there is an obvious interaction between fire and herbivores (Archibald et al., 2005; Roques et al., 2001), we investigated the impact of fire on wild large herbivores. Specifically, we investigated habitat and species selection by large herbivores with respect to fire history. Additionally, we investigated the differences in the nutritional quality of the selected species in relation to fire history.

Methods

We investigated differences in the habitat utilization of twelve herbivorous mammals between sites of different fire histories using faecal pellet counts along the transects previously described. This cost-effective method is widely accepted not only for assessing habitat utilization but also for estimating population numbers (Archibald et al., 2005; Barnes & Guenda, 2013; Isaacs et al., 2013; Månsson et al., 2011). It is a particularly useful method in habitats with dense vegetation, such as the treatments that had not burned for many years. Barnes & Guenda (2013) showed that this method is even more accurate than aerial surveys or direct counts. There are some disadvantages, however, as it is not suitable for animals using latrines (e.g., rhino) and there might be a bias if there are large populations of different dung beetle species present, as is the case at WPP (Fig. 8). Dung beetles can be quite selective (with a high preference for moist dung such as rhino or buffalo dung), especially during the wet season. During this study, buffalo dung pats were completely removed and covered within a day. To estimate population numbers and compare utilization rates of different herbivore species, which was not part of our study, the accurate defecation rate of a species is required. For example, the

Figure 9: Home ranges (red margins) of buffalo herds in relation to recent fire history in the park. The left hand images (a), (c), (e) and (g) right hand images (b), (d), (f) and (h).The dots (yellow for Herd 1 and red for Herd 2) show the locations of the marked animals during the time period.

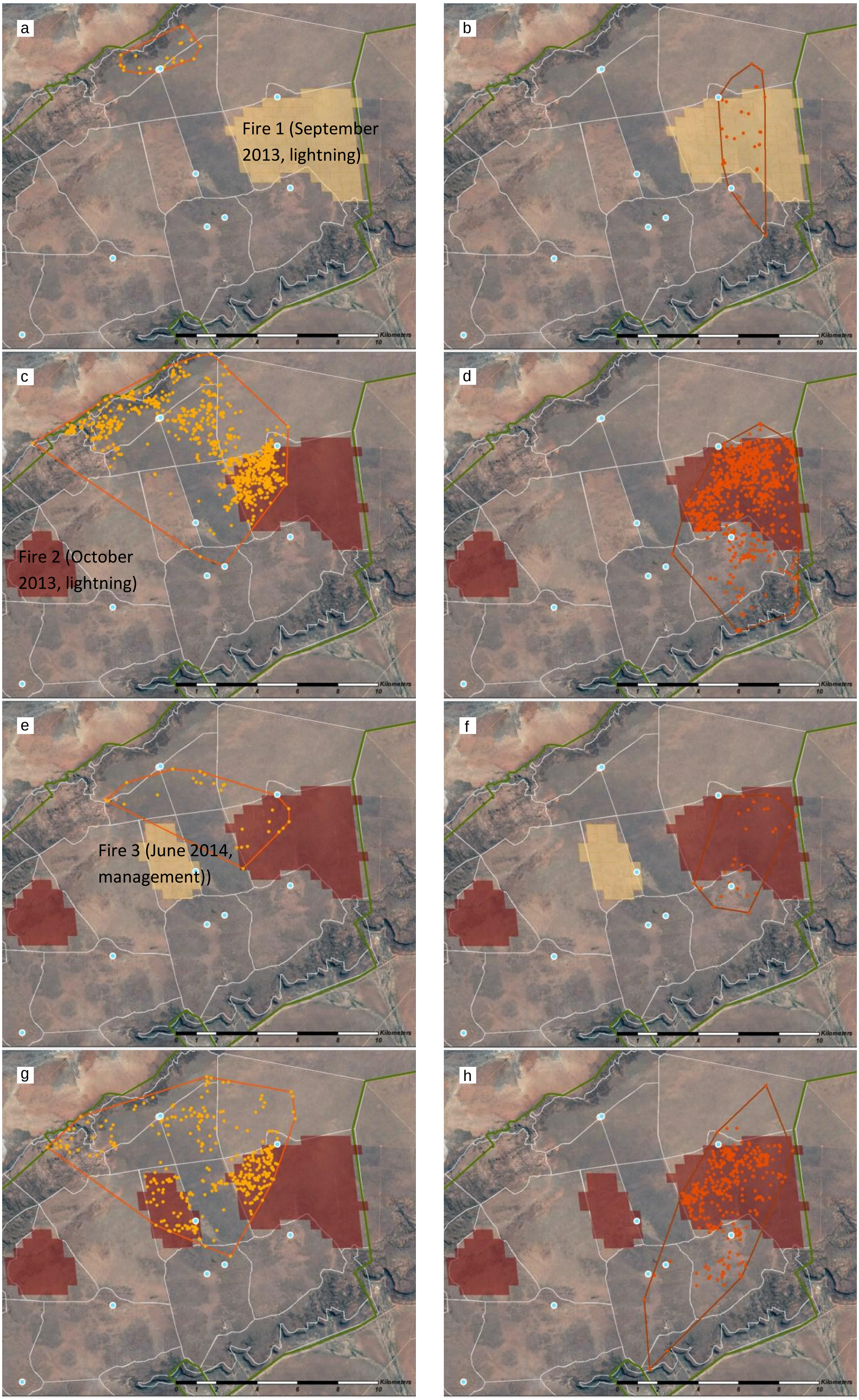
a) and b) at the time of Fire 1 (lightning fire, September 2013). Herds separate and the fire occurs in the core of Herd 2's home range.

c) and d) during January to March 2014. Herd 1 has shifted its home range to include the Fire 1 patch whilst Herd 2 is strongly focussed on Fire 1 patch. Some spatial overlap between the herds occurs in the burned area. Fire 2 has occurred in October 2013, but the burned patch has not been utilised by either herd.

e) and f) at the time of Fire 3 (a management burn in June 2014). The situation is very similar to the summer grazing shown in c) and d). Fire 2 patch still avoided by both herds.

g) and h) during October to December 2014. Herd 1 now utilises both Fire 1 patch and Fire 3 patch. Herd 2 remains concentrated on Fire 1 patch. The Fire 2 patch is not utilised.

Figure 8: Numerous large dung beetles (*Pachylomerus femoralis*) utilizing rhinoceros dung in the study area.


a
b
c
d
e
f
g
h
Fire 1 (September 2013, lightning)
Fire 2 (October 2013, lightning)
Fire 3 (June 2014, management))

defecation rate of buffalo is quite low (5–1 dung heaps per day; Plumptre & Harris, 1995), whereas the rate for kudu is quite high (24 faecal groups per day; Ellis & Bernard, 2005). In this study we were more interested in comparing the relative utilization of different fire treatments by each species, rather than comparing the absolute numbers of each herbivore species. Along each 200 m transect, dung counts were done at every 20 m within a 4 m x 8 m quadrat. Pellet counting was standardized to ten pellets to be counted as an individual animal. Within each 4 m x 8 m quadrant corner, each nearest shrub, weed, and grass was identified, recorded, and observed for grazing and browsing damage (Uunona, 2014). From these data, the total amount of feeding damage per species was assessed, as was preference (the proportion of each species showing feeding damage). Additionally, we installed camera traps to get an understanding of herd size and population structure as well as the occurrence of predators. We also analysed the nutritional quality of known food plants on sites with different fire histories.

Furthermore, we placed GPS collars on collared four African buffalos (*Syncerus caffer*) from three different herds in September 2013 and tracked their utilization of the different fire treatments for close to two years. We were able to track two of the herds that were adjacent to each other and in the study area. From this we were able to visualize their home ranges and different responses to fire history.

Results

1. What kind of habitat was used by large herbivores in relation to fire?

As expected, most of the animal species utilized the recently burned site the most (block 1, burned in 2013, investigated in 2014). Warthog and oryx, both low in abundance, were found only in this area. Others, such as giraffe, kudu, sable, and roan, also showed a clear preference for this site. The results were similar for eland and buffalo, but the differences in dung counts were not significant. Utilization by buffalo is most likely underestimated due to the large population of dung beetles in the study area. Dung beetles remove and bury the soft dung pats of buffalo in less than a day (Fig. 8). However, the preference for this area by buffalo is clearly evident in Fig. 9 which show the utilization of burned areas by the GPS-collared buffaloes. Furthermore, our camera traps showed high rates of utilization of the recently burned area by large eland herds (Fig. 10). Both grazers and browsers preferred this recently burned area. Interestingly, the site in the direct neighbourhood of the recently burned site, which was burned 14 years ago (at the time of the measurements, block 3), was the site that was second most strongly utilized and preferred over the site that was burned only two years ago (block 2) for most species, with the exception of warthog and oryx. One can assume that the same individuals were using the recently burned area (block 1) for feeding and the "unburned" area (block 3) for ruminating and resting in the shade, and possibly predator avoidance, as this side had much more canopy and denser vegetation. This kind of dense vegetation was also preferred by small ungulates, such as duiker and steenbok, as well as hares. The overall pattern of high utilization of the burned sites persisted into the next year of our investigation (2015). Importantly, buffalo herds only shifted their home ranges to utilise burned areas adjacent to their pre-fire home ranges (Fig. 9).

2. What has been eaten?

Large herbivores preferred feeding on grasses and trees at the recently burned site, with a higher utilization of trees/shrubs compared to grasses (block 1). The second highest levels of herbivory were found in the area burned a year earlier (block 2). However, these levels were much lower than at the recently burned site. In burned areas, some grass and tree species were 100 % utilized e.g. utilisation of all sampled individuals (e.g., *B. nigropedata*, *P. kalaharense*, *G. flavescens*, and *Philenoptera nelsii*). However, *B. nigropedata* and *P. nelsii* were not abundant despite being preferred, so the most utilized grass species were *D. seriata* (highly palatable), *A. stipitata*, and *S. uniplumis* (relatively unpalatable) and the most utilized tree/shrub species were *T. sericea*, *Bauhinia petersiana*, and *A. ataxacantha*. Our survey of feeding damage underscores our results from the habitat utilization survey: plants were utilized the most in the burned area (burned recently, block 1). However, we found almost no feeding damage on the neighbouring site (burned long ago, block 3). This supports the suggestion that the neighbouring site is used mainly for resting and ruminating.

Figure 10: Camera trap image (taken two years after the fire) of eland in the recently burned area (block 1) feeding on resprouting P. nelsi (Image: C.Stolter).

Figure 11: Camera trap image taken two years after the fire) showing a hartebeest (a typical grazer) browsing on tree resprout (Image: C.Stolter).


Figure 12: Heavily browsed resprout of T. sericea (Image: C.Stolter).

3. How does fire affect the nutritional quality of the plant?

We found that the leaves of tree species are generally higher in protein concentration compared to grasses. Looking at the most utilized grasses and trees, we discovered that they are of medium quality. Some heavily utilized species (the grass *B. nigropetata* and the tree *P. nelsii*) had higher protein and hemicellulose concentrations compared to less preferred species. Food selection is further described in the info box about food quality for ruminants and discussed in the chapter on food quality and availability for large herbivores (Stolter et al., 2018).

The nutritional quality of grasses was not different between the recently burned site (block 1, sampled two years after burning in 2015) and the neighbouring site, burned 15 years ago (block 3). In contrast to grasses, almost all tree species showed higher protein concentrations at the recently burned site (block 1, sampled two years after burning in 2015). In dry seasons or periods with restricted grass availability, then, the resprouting of the trees after a fire event might serve as high-quality food not only to browsers but also to grazers (Fig. 11, Fig. 12). However, more investigations of food selection are needed here.

Synthesis and outlook

What can we learn from it? Recently burned sites attract both grazers and browsers. However, neighbouring sites with dense vegetation seem to be important as well. Grazers and browsers use recently burned sites for feeding and the “unburned” neighbouring site for resting (ruminating) and perhaps predator avoidance. Smaller species, however, prefer unburned sites with dense vegetation for feeding and resting. These relatively small herbivores can move easily between the bushes, so the dense vegetation offers them good protection and less competition with larger herbivores. Interestingly, as a result of territorial buffalo behaviour, the two herds show almost no overlap in utilization. Newly burned areas were used by buffaloes only if the areas were part of or close to their pre-fire home range. This was not realised by park managers until these results were shown. This has profound implications for the management of the spatial arrangement of fires in the park.

After burning, grasses and trees/shrubs are heavily utilized by different large herbivores, with a pronounced higher utilization of trees/shrubs. The time since last burning changes the nutritional composition of both plant types (trees and grasses). While grasses did not differ in nutritional composition between sites with different fire histories, tree leaves remained higher in protein concentration for a longer period. Similar plant responses are known from post-herbivory processes on trees (see also the chapter on food quality and availability of large herbivores, Stolter et al., 2018; Stolter, 2008). Hence, they are an important food resource even for grazing animals, which was reflected in their high utilization. At the time of sampling, animal utilization of this site (block 1, two years after burning) was still high. This implies that the most frequently burned site will be the most attractive until another site is burned. Nevertheless, the site has to be situated in the home range or territory of the animal of interest. Concerning the general quality of a burned site compared to unburned sites, one must consider that there are far fewer moribund grasses in a burned area, which might enhance the overall quality.

Why is this interesting? The findings illustrate that heterogeneous habitats, through pyrodiversity, are beneficial for wild ungulates. Even typical grazers utilize neighbouring areas with dense vegetation. Recently burned areas provide higher-quality food, but neighbouring dense vegetation is important for ruminating or resting as well as serving as habitat for species not adapted to open habitats. The most recently burned site will frequently be used for feeding as long as there is no other burned site nearby. The influence of burning on the quality of grasses is relatively short-lived, but the overall quality might be enhanced on the recently burned site because of the presence of a lower proportion of moribund grasses. Trees provide foliage, which is generally higher in protein and serves as a supplementary food source of higher quality after a fire (for at least two years after burning). This might be of special importance in periods of low food supply. In this respect, we need a better understanding of wild herbivores' food selection and plant responses to fire and herbivory. The knowledge gained from this study and future research will enable us to manage livestock and game in coexistence.

Acknowledgements

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References

Anderson, T.M., Ritchie, M.E., Mayemba, E., Eby, S., Grace, J.B. & McNaughton, S.J. (2007) Forage nutritive quality in the Serengeti ecosystem: the roles of fire and herbivory. *The American Naturalist*, **170**, 343–357.

Archibald, S., Bond, W., Stock, W. & Fairbanks, D. (2005) Shaping the landscape: fire–grazer interactions in an African savanna. *Ecological Applications*, **15**, 96–109.

Barnes, R.F. & Guenda, W. (2013) Elephants or excrement? Comparison of the power of two survey methods for elephants in West African savanna. *Environment and Pollution*, **2**, 14.

Campbell, J.W. & Hanula, J.L. (2007) Efficiency of Malaise traps and colored pan traps for collecting flower-visiting insects from three-forested ecosystems. *Journal of Insect Conservation*, **11**, 399–408.

Coetsee, C., Bond, W.J. & February, E.C. (2010) Frequent fire affects soil nitrogen and carbon in an African savanna by changing woody cover. *Oecologia*, **162**, 1027–1034.

Concilio, A., Ma, S., Ryu, S., North, M. & Chen, J. (2006) Soil respiration response to experimental disturbances over 3 years. *Forestry Ecology and Management*, **228**, 82–90.

Cottam, G. & Curtis, J.T. (1956) The use of distance measures in phytosociological sampling. *Ecology*, **37**, 451–460.

Davies, A.B., Parr, C.L., Rensburg, V. & Berndt, J. (2010) Termites and fire: current understanding and future research directions for improved savanna conservation. *Austral Ecology*, **35**, 482–486.

de Graaff, M.A., Throop, H.L., Verburg, P.S.J., Arnone, J.A. & Campos, X. (2014) A synthesis of climate and vegetation cover effects on biogeochemical cycling in shrub-dominated

Rangelands

drylands. *Ecosystems*, **17**, 931–945. https://doi.org/10.1007/s10021-014-9764-6

Eardley, C., Kuhlmann, M. & Pauly, A. (2010) *The bee genera and subgenera of sub-Saharan Africa*. Belgian Development Cooperation, Brussels.

Ellis, A.M. & Bernard, R.T. (2005) Estimating the density of kudu (*Tragelaphus strepsiceros*) in subtropical thicket using line transect surveys of dung and DISTANCE software. *African Journal of Ecology*, **43**, 362–368.

Erb, K.P. (1993) *The roan antelope (*Hippotragus equinus, *Desmarest 1804), its ecology in the Waterberg Plateau Park*. Unpublished master's thesis, Stellenbosch University, South Africa.

Erckie, J.B. (2007) *Assessing the effects of grazing intensity by large herbivores on species diversity and abundance of small mammals at Waterberg Plateau Park, Namibia*. Unpublished master's thesis, University of Namibia.

Friedel, M. & Chewings, V. (1988) Comparison of crown cover estimates for woody vegetation in arid rangelands. *Austral Ecology*, **13**, 463–468.

Giess, W. (1971) A preliminary vegetation map of South West Africa. *Dinteria*, 1971, 5–14.

Greenleaf, S.S., Williams, N.M., Winfree, R. & Kremen, C. (2007) Bee foraging ranges and their relationship to body size. *Oecologia*, **153**, 589–596.

Hammer, Ø., Harper, D., and Ryan, P. (2001) PAST: Paleontological Statistics software package for education and data analysis. *Palaeontologia Electronica*, **4**, 1–9.

Han, G., Xing, Q., Luo, Y., Rafique, R., Yu, J. & Mikle, N. (2014) Vegetation types alter soil respiration and its temperature sensitivity at the field scale in an estuary wetland. *PLOS One*, 9. https://doi.org/10.1371/journal.pone.0091182.

Hanula, J.L. & Wade, D.D. (2003) Influence of long-term dormant-season burning and fire exclusion on ground-dwelling arthropod populations in longleaf pine flatwoods ecosystems. *Forest Ecology and Management*, **175**, 163–184.

Higgins, S.I., Bond, W.J., February, E.C., Bronn, A., Euston-Brown, D.I., Enslin, B., Govender, N., Rademan, L., O'Regan, S. & Potgieter, A.L. (2007) Effects of four decades of fire manipulation on woody vegetation structure in savanna. *Ecology*, **88**, 1119–1125.

Holdo, R.M., Mack, M.C. & Arnold, S.G. (2012) Tree canopies explain fire effects on soil nitrogen, phosphorus and carbon in a savanna ecosystem. *Journal of Vegetation Science*, **23**, 352–360.

Holt, J.A. & Coventry, R.J. (1990) Nutrient cycling in Australian savannas. *Journal of Biogeography*, **17**, 427–432.

Isaacs, L., Somers, M.J. & Dalerum, F. (2013) Effects of prescribed burning and mechanical bush clearing on ungulate space use in an African savannah. *Restoration Ecology*, **21**, 260–266.

Jankowitz, W.J. (1983) *Die plantekologie van die Waterberg Platopark*. Unpublished PhD thesis, University of the Free State, South Africa.

Joubert, D., Smit, G. & Hoffman, M. (2012) The role of fire in preventing transitions from a grass-dominated state to a bush-thickened state in arid savannas. *Journal of Arid Environments*, **87**, 1–7.

Joubert, D.F., Powell, L.A., Schacht, W.H. (2015) Visual obstruction as a method to quantify herbaceous biomass in southern African semi-arid savannas. *African Journal of Range and Forage Science*, **32**, 225–230.

Khavhagali, V.P. (2008) *Forest colonization of savannas: patterns and process*. Unpublished MSc. thesis, University of Cape Town, South Africa.

Månsson, J., Andrén, H. & Sand, H. (2011) Can pellet counts be used to accurately describe winter habitat selection by moose *Alces alces*? *European Journal of Wildlife Research*, **57**, 1017–1023.

McCune, B. & Mefford, M.J. (2011) *PC-ORD for windows. Multivariate analysis of ecological data.* Version 6. MjM Software, Gleneden Beach, Oregon, USA.

McNaughton, S., Ruess, R. & Seagle, S. (1988) Large mammals and process dynamics in African ecosystems. *BioScience*, **38**, 794–800.

Michener, C.D. (2007) *The bees of the world*, 2nd ed. Johns Hopkins University Press, Baltimore.

Mitchell, K. (2007) *Quantitative analysis by the point-centered quarter method.* Department of Mathematics and Computer Science, Hobart and William Smith Colleges, Geneva, NY, USA.

Mukaru, W.C. (2009) *Impacts of large herbivores on vegetation and soils around water points in Waterberg Plateau Park, Central Namibia*. Unpublished master's thesis, University of Namibia.

Olff, H. & Ritchie, M.E. (1998) Effects of herbivores on grassland plant diversity. *Trends in Ecology & Evolution*, **13**, 261–265.

Oliver, I. & Beattie, A.J. (1996) Invertebrate morphospecies as surrogates for species: a case study. *Conservation Biology*, **10**, 99–109.

Osborne, C.P. (2008) Atmosphere, ecology and evolution: what drove the Miocene expansion of C4 grasslands? *Journal of Ecology*, **96**, 35–45.

Pickett, S.T. (1989) Space-for-time substitution as an alternative to long-term studies. *Long-term studies in ecology*, pp. 110–135. Springer, New York, NY

Plumptre, A. & Harris, S. (1995) Estimating the biomass of large mammalian herbivores in a tropical montane forest: a method of faecal counting that avoids assuming a steady state system. *Journal of Applied Ecology*, **32**, 111–120.

Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O. & Kunin, W.E. (2010) Global pollinator declines: trends, impacts and drivers. *Trends in Ecology & Evolution*, **25**, 345–353.

R Core Team (2017) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Roques, K., O'Connor, T. & Watkinson, A. (2001) Dynamics of shrub encroachment in an African savanna: relative influences of fire, herbivory, rainfall and density dependence. *Journal of Applied Ecology*, **38**, 268–280.

Satyam, V. & Jayakumar, S. (2012) Impact of forest fire on physical, chemical and biological properties of soil: A review. *Proceedings of the International Academy of Ecology and Environmental Sciences*, **2**, 168–176.

Schneider, I. (1993) *Waterberg Plateau Park.* Shell Namibia.

Robel, R.J., Briggs, J.N., Dayton, A.D., Hulbert, L.C. (1970) Relationships between visual obstruction measurements and weight of grassland vegetation. *Journal of Range Management*, **23**, 295–297.

Stolter, C. (2008). Intra-individual plant response to moose browsing: feedback loops and impacts on multiple consumers. *Ecological Monographs*, **78**, 167–183.

Stolter, C., Ramoelo, A., Kesch, K., Madibela, O., Cho, M.A. & Joubert, D. (2018a) Forage quality and availability for large herbivores in southern African rangelands. This volume.

Trollope, W.S.W., Trollope, L.A., Goode, R., de Bruyn, P. & van den Broeck, D. (2013). Assessment of veld condition using the adapted point centred quarter method for bush surveys. *Special Report — Research & Development, Working on Fire, South Africa*, pp. 1–20.

Uresk, D.W., Mergen, D.E. & Benzon, T.A. (2009) Estimating standing vegetation with a modified Robel pole on meadows and grasslands in southern Black Hills of South Dakota. *Proceedings of the South Dakota Academy of Science*, **88**, 91–97.

Uunona, N. (2014) Resource utilisation of large herbivores in the Waterberg Plateau Park. Unpublished BSc project, Namibia University of Science and Technology.

Van Nuland, M.E., Haag, E.N., Bryant, J.A., Read, Q.D., Klein, R.N., Douglas, M.J., Gorman, C.E., Greenwell, T.D., Busby, M.W., Collins, J., LeRoy, J.T., Schuchmann, G., Schweitzer, J.A. & Bailey, J.K. (2013) Fire promotes pollinator visitation: implications for ameliorating declines of pollination services. *PLOS One*, **8**, e79853.

van Wilgen, B.W. (2009) The evolution of fire management practices in savanna protected areas in South Africa. *South African Journal of Science*, **105**, 343–349.

Westphal, C., Bommarco, R., Carré, G., Lamborn, E., Morison, N., Petanidou, T., Potts, S.G., Roberts, S.P., Szentgyörgyi, H. & Tscheulin, T. (2008) Measuring bee diversity in different European habitats and biogeographical regions. *Ecological Monographs*, **78**, 653–671.

Work, T.T., Buddle, C.M., Korinus, L.M. & Spence, J.R. (2002) Pitfall trap size and capture of three taxa of litter-dwelling arthropods: implications for biodiversity studies. *Environmental Entomology*, **31**, 438–448.

Zimmermann, I. & Mwazi, F.N. (2002) The effect of a prescribed burn, followed up with browsing pressure, on rangeland condition in the mountain savanna and karstveld of Namibia, Namibia. *Dinteria*, **27**, 49–57.

References [CrossRef]

Anderson, T.M., Ritchie, M.E., Mayemba, E., Eby, S., Grace, J.B. & McNaughton, S.J. (2007) Forage nutritive quality in the Serengeti ecosystem: the roles of fire and herbivory. *The American Naturalist*, **170**, 343–357. CrossRef

Archibald, S., Bond, W., Stock, W. & Fairbanks, D. (2005) Shaping the landscape: fire–grazer interactions in an African savanna. *Ecological Applications*, **15**, 96–109. CrossRef

Barnes, R.F. & Guenda, W. (2013) Elephants or excrement? Comparison of the power of two survey methods for elephants in West African savanna. *Environment and Pollution*, **2**, 14.

Campbell, J.W. & Hanula, J.L. (2007) Efficiency of Malaise traps and colored pan traps for collecting flower-visiting insects from three-forested ecosystems. *Journal of Insect Conservation*, **11**, 399–408. CrossRef

Coetsee, C., Bond, W.J. & February, E.C. (2010) Frequent fire affects soil nitrogen and carbon in an African savanna by changing woody cover. *Oecologia*, **162**, 1027–1034. CrossRef

Concilio, A., Ma, S., Ryu, S., North, M. & Chen, J. (2006) Soil respiration response to experimental disturbances over 3 years. *Forestry Ecology and Management*, **228**, 82–90. CrossRef

Cottam, G. & Curtis, J.T. (1956) The use of distance measures in phytosociological sampling. *Ecology*, **37**, 451–460. CrossRef

Davies, A.B., Parr, C.L., Rensburg, V. & Berndt, J. (2010) Termites and fire: current understanding and future research directions for improved savanna conservation. *Austral Ecology*, **35**, 482–486. CrossRef

de Graaff, M.A., Throop, H.L., Verburg, P.S.J., Arnone, J.A. & Campos, X. (2014) A synthesis of climate and vegetation cover effects on biogeochemical cycling in shrub-dominated drylands. *Ecosystems*, **17**, 931–945. CrossRef

Eardley, C., Kuhlmann, M. & Pauly, A. (2010) *The bee genera and subgenera of sub-Saharan Africa*. Belgian Development Cooperation, Brussels.

Ellis, A.M. & Bernard, R.T. (2005) Estimating the density of kudu (*Tragelaphus strepsiceros*) in subtropical thicket using line transect surveys of dung and DISTANCE software. *African Journal of Ecology*, **43**, 362–368. CrossRef

Erb, K.P. (1993) *The roan antelope (*Hippotragus equinus, *Desmarest 1804), its ecology in the Waterberg Plateau Park*. Unpublished master's thesis, Stellenbosch University, South Africa.

Erckie, J.B. (2007) *Assessing the effects of grazing intensity by large herbivores on species diversity and abundance of small mammals at Waterberg Plateau Park, Namibia*. Unpublished master's thesis, University of Namibia.

Friedel, M. & Chewings, V. (1988) Comparison of crown cover estimates for woody vegetation in arid rangelands. *Austral Ecology*, **13**, 463–468. CrossRef

Giess, W. (1971) A preliminary vegetation map of South West Africa. *Dinteria*, **1971**, 5–14.

Greenleaf, S.S., Williams, N.M., Winfree, R. & Kremen, C. (2007) Bee foraging ranges and their relationship to body size. *Oecologia*, ***153***, 589–596. CrossRef

Hammer, Ø., Harper, D., and Ryan, P. (2001) PAST: Paleontological Statistics software package for education and data analysis. *Palaeontologia Electronica*, **4**, 1–9.

Han, G., Xing, Q., Luo, Y., Rafique, R., Yu, J. & Mikle, N. (2014) Vegetation types alter soil respiration and its temperature sensitivity at the field scale in an estuary wetland. *PLOS One*, **9**. CrossRef

Hanula, J.L. & Wade, D.D. (2003) Influence of long-term dormant-season burning and fire exclusion on ground-dwelling arthropod populations in longleaf pine flatwoods ecosystems. *Forest Ecology and Management*, **175**, 163–184. CrossRef

Higgins, S.I., Bond, W.J., February, E.C., Bronn, A., Euston-Brown, D.I., Enslin, B., Govender, N., Rademan, L., O'Regan, S. & Potgieter, A.L. (2007) Effects of four decades of fire manipulation on woody vegetation structure in savanna. *Ecology*, **88**, 1119–1125. CrossRef

Holdo, R.M., Mack, M.C. & Arnold, S.G. (2012) Tree canopies explain fire effects on soil nitrogen, phosphorus and carbon in a savanna ecosystem. *Journal of Vegetation Science*, **23**, 352–360. CrossRef

Holt, J.A. & Coventry, R.J. (1990) Nutrient cycling in Australian savannas. *Journal of Biogeography*, **17**, 427–432. CrossRef

Isaacs, L., Somers, M.J. & Dalerum, F. (2013) Effects of prescribed burning and mechanical bush clearing on ungulate space use in an African savannah. *Restoration Ecology*, **21**, 260–266. CrossRef

Jankowitz, W.J. (1983) *Die plantekologie van die Waterberg Platopark*. Unpublished PhD thesis, University of the Free State, South Africa.

Joubert, D., Smit, G. & Hoffman, M. (2012) The role of fire in preventing transitions from a grass-dominated state to a bush-thickened state in arid savannas. *Journal of Arid Environments*, **87**, 1–7. CrossRef

Joubert, D.F., Powell, L.A., Schacht, W.H. (2015) Visual obstruction as a method to quantify herbaceous biomass in southern African semi-arid savannas. *African Journal of Range and Forage Science*, **32**, 225–230. CrossRef

Khavhagali, V.P. (2008) *Forest colonization of savannas: patterns and process*. Unpublished MSc. thesis, University of Cape Town, South Africa.

Månsson, J., Andrén, H. & Sand, H. (2011) Can pellet counts be used to accurately describe winter habitat selection by moose *Alces alces*? *European Journal of Wildlife Research*, **57**, 1017–1023. CrossRef

McCune, B. & Mefford, M.J. (2011) *PC-ORD for windows. Multivariate analysis of ecological data*. Version 6. MjM Software, Gleneden Beach, Oregon, USA.

McNaughton, S., Ruess, R. & Seagle, S. (1988) Large mammals and process dynamics in African ecosystems. *BioScience*, **38**, 794–800. CrossRef

Michener, C.D. (2007) *The bees of the world*, 2nd ed. Johns Hopkins University Press, Baltimore.

Mitchell, K. (2007) *Quantitative analysis by the point-centered quarter method.* Department of Mathematics and Computer Science, Hobart and William Smith Colleges, Geneva, NY, USA.

Mukaru, W.C. (2009) *Impacts of large herbivores on vegetation and soils around water points in Waterberg Plateau Park, Central Namibia*. Unpublished master's thesis, University of Namibia.

Olff, H. & Ritchie, M.E. (1998) Effects of herbivores on grassland plant diversity. *Trends in Ecology & Evolution*, **13**, 261–265. CrossRef

Oliver, I. & Beattie, A.J. (1996) Invertebrate morphospecies as surrogates for species: a case study. *Conservation Biology*, **10**, 99–109. CrossRef

Osborne, C.P. (2008) Atmosphere, ecology and evolution: what drove the Miocene expansion of C4 grasslands? *Journal of Ecology*, **96**, 35–45.

Pickett, S.T. (1989) Space-for-time substitution as an alternative to long-term studies. *Long-term studies in ecology*, pp. 110–135. Springer, New York, NY

Plumptre, A. & Harris, S. (1995) Estimating the biomass of large mammalian herbivores in a tropical montane forest: a method of faecal counting that avoids assuming a steady state system. *Journal of Applied Ecology*, **32**, 111–120. CrossRef

Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O. & Kunin, W.E. (2010) Global pollinator declines: trends, impacts and drivers. *Trends in Ecology & Evolution*, **25**, 345–353. CrossRef

R Core Team (2017) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Roques, K., O'Connor, T. & Watkinson, A. (2001) Dynamics of shrub encroachment in an African savanna: relative influences of fire, herbivory, rainfall and density dependence. *Journal of Applied Ecology*, **38**, 268–280. CrossRef

Satyam, V. & Jayakumar, S. (2012) Impact of forest fire on physical, chemical and biological properties of soil: A review.

Proceedings of the International Academy of Ecology and Environmental Sciences, **2**, 168–176.

Schneider, I. (1993) *Waterberg Plateau Park*. Shell Namibia.

Robel, R.J., Briggs, J.N., Dayton, A.D., Hulbert, L.C. (1970) Relationships between visual obstruction measurements and weight of grassland vegetation. *Journal of Range Management*, **23**, 295–297. CrossRef

Stolter, C. (2008). Intra-individual plant response to moose browsing: feedback loops and impacts on multiple consumers. *Ecological Monographs*, **78**, 167–183. CrossRef

Stolter, C., Ramoelo, A., Kesch, K., Madibela, O., Cho, M.A. & Joubert, D. (2018a) Forage quality and availability for large herbivores. This volume. CrossRef

Trollope, W.S.W., Trollope, L.A., Goode, R., de Bruyn, P. & van den Broeck, D. (2013). Assessment of veld condition using the adapted point centred quarter method for bush surveys. *Special Report — Research & Development, Working on Fire, South Africa*, pp. 1–20.

Uresk, D.W., Mergen, D.E. & Benzon, T.A. (2009) Estimating standing vegetation with a modified Robel pole on meadows and grasslands in southern Black Hills of South Dakota. *Proceedings of the South Dakota Academy of Science*, **88**, 91–97.

Uunona, N. (2014) Resource utilisation of large herbivores in the Waterberg Plateau Park. Unpublished BSc project, Namibia University of Science and Technology.

Van Nuland, M.E., Haag, E.N., Bryant, J.A., Read, Q.D., Klein, R.N., Douglas, M.J., Gorman, C.E., Greenwell, T.D., Busby, M.W., Collins, J., LeRoy, J.T., Schuchmann, G., Schweitzer, J.A. & Bailey, J.K. (2013) Fire promotes pollinator visitation: implications for ameliorating declines of pollination services. *PLOS One*, **8,** e79853. CrossRef

van Wilgen, B.W. (2009) The evolution of fire management practices in savanna protected areas in South Africa. *South African Journal of Science*, **105**, 343–349.

Westphal, C., Bommarco, R., Carré, G., Lamborn, E., Morison, N., Petanidou, T., Potts, S.G., Roberts, S.P., Szentgyörgyi, H. & Tscheulin, T. (2008) Measuring bee diversity in different European habitats and biogeographical regions. *Ecological Monographs*, **78**, 653–671. CrossRef

Work, T.T., Buddle, C.M., Korinus, L.M. & Spence, J.R. (2002) Pitfall trap size and capture of three taxa of litter-dwelling arthropods: implications for biodiversity studies. *Environmental Entomology*, **31**, 438–448. CrossRef

Zimmermann, I. & Mwazi, F.N. (2002) The effect of a prescribed burn, followed up with browsing pressure, on rangeland condition in the mountain savanna and karstveld of Namibia, Namibia. *Dinteria*, **27**, 49-57.

Impact of bush encroachment management on plant response and animal distribution

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Abstract: The transformation of grassland by bush encroachment causes socioeconomic problems in arid and semi-arid regions. At the moment, de-bushing is the only way to control bush encroachment. In this context, we conducted two independent projects within SASSCAL. First, in a greenhouse experiment, we investigated the morphological plant response to damage of four different bush encroacher species in order to understand if intervention in the plants' early life stage may reasonably fight bush encroachment and if treated plants are used differently by livestock (e.g., sheep and goats). In a second project, we investigated the influence of bush clearing on the habitat utilisation of different large herbivores (e.g., greater kudu, warthog, and gemsbok). Specifically, we wanted to know if typical grazers (e.g., warthog and gemsbok) are found at open cleared sites and typical browsers (greater kudu) in encroached regions and if vegetation parameters (e.g., grass cover) drive this distribution. For our greenhouse experiment, we found that all seedlings reacted morphologically to the damage of top-shoots, but to different extents. Damaged plants show species-specific responses, like differences in branching and thorn sizes and survival rates. In contrast to sheep, goats were not absolutely deterred by mechanical defences of the offered plant species. Therefore, we assume that under controlled grazing regimes, goat feeding could be a useful tool to interfere with the establishment of large numbers of seedlings. In our second project, the animal distribution did not consistently match our expectations. While warthog and cattle shared open bush-cleared sites, we found gemsbok utilising non-cleared sites with high thornbush cover of medium height, which was similar to patterns shown by greater kudu. The results are discussed in light of competition, risk avoidance, and habitat heterogeneity.

Resumo: A transformação dos prados pela densificação de plantas lenhosas causa problemas socioeconómicos em regiões áridas e semi-áridas. De momento, a remoção de plantas lenhosas é a única maneira de controlar a sua densificação. Assim, conduzimos dois projectos independentes no contexto do SASSCAL. Numa experiência numa estufa, investigámos a resposta morfológica a danos de quatro espécies invasoras diferentes, de modo a compreender se a intervenção no estádio inicial de vida é razoável para combater a invasão das lenhosas, bem como se estas plantas tratadas são usadas de forma diferente pelo gado (ovelhas e cabras). Num segundo projecto, investigámos a influência do desmatamento na utilização do habitat por diferentes grandes herbívoros (cudo, javali-africano e órix). Especificamente, queriamos saber se típicos herbívoros de pasto (e.x.: javali-africano e órix) eram encontrados em locais abertos, e típicos *browsers* (cudo) em regiões invadidas, e se os parâmetros da vegetação (e.x.: cobertura de gramíneas) conduzem esta distribuição. Na nossa experiência na estufa, descobrimos que todas as plântulas reagiram morfologicamente, mas em extensões diferentes aos danos dos rebentos superiores. As plantas danificadas mostram respostas específicas à espécie, tais como diferenças na ramificação, tamanho dos espinhos e taxas de sobrevivência. Em contraste com as ovelhas, as cabras não foram de todo dissuadidas pelas defesas mecânicas das espécies de plantas oferecidas. Desta forma, assumimos que, sob regimes de pastagem controlados, a alimentação de cabras pode ser uma ferramenta útil para interferir no estabelecimento de grandes números de plântulas. No nosso segundo projecto, a distribuição animal não correspondeu invariavelmente às nossas expectativas. Enquanto que o javali-africano e o gado partilharam locais desmatados abertos, observámos o órix a utilizar locais não desmatados com uma elevada cobertura de plantas espinhosas de altura média, semelhante ao cudu. Os resultados são discutidos à luz da competição, prevenção de riscos e heterogeneidade do habitat.

Introduction

Savannas are important ecosystems, as they hold one-fifth of the world's human population and the most livestock and other large herbivores (Graz, 2008). Due to the enormous rangelands covered by savannas, these ecosystems are also of high economic value. Furthermore, they bear a high value of cultural services, not only for indigenous people but also for tourism. Here, people have the increasingly rare opportunity to watch the spectacular diversity of wild large herbivores. Nowadays, tourism contributes a significant share to the gross national product of southern Africa. However, at the moment, the world's savannas are undergoing rapid and radical human-induced transformation (Lehmann et al., 2009) caused by bush encroachment. Bush encroachment is described as the increase of biomass, cover, and abundance of woody plant species, accompanied by the suppression of perennial grasses and herbs (Ward, 2005; O'Connor et al., 2014). The reasons for the increasing numbers of tree species outcompeting grasses are multiple and complex, and are mainly ascribed to poor management of farmland, including overgrazing (Skarpe, 1990; Scholes & Archer, 1997; Lange et al., 1998), the suppression of fires (Scholes & Archer, 1997; Joubert et al., 2008), and the absence of browsers (e.g., Staver et al., 2009). Other drivers such as climate change and increased CO_2 levels have also been identified (e.g. Archer et al., 1995; Ward, 2005; Bond, 2008).

The consequence of this transformation is a reduced grazing capacity of herbivores including livestock, which might also lead to enhanced soil erosion and desertification (De Klerk, 2004; Stevens et al., 2017). Furthermore, due to the limitation of sight, the visibility of wild herbivores is reduced which might lead to negative consequences for tourism. Even though bush encroachment has some beneficial aspects (e.g., the accumulation of carbon in the standing biomass and the possibility of charcoal production), the transformation of grassland by bush encroachment causes socio-economic problems in arid and semi-arid regions to an extent that many previously profitable areas are no longer economically viable (Smit, 2004).

At the moment de-bushing is the only way to control bush encroachment and to maintain the economically and ecologically valuable open savanna ecosystems. Therefore, farmers use a variety of methods to fight bush encroachment (de Wet, 2015). Because of the high costs of these interventions (for example, beef producers in Namibia spend about US $54 million per year; De Klerk, 2004), there is a great agreement in the affected countries regarding the need to develop sustainable management options to suppress bush encroachment. In this context, we conducted two independent projects. The first project presented here deals with the impact of mechanical cutting of bush encroacher species seedlings. Reducing the density of bush encroacher species through intervention in the early life stage of the plants is a reasonable potential intervention. As cutting and/or grazing are appropriate management tools, we tested the plant response to damage of four different bush encroacher species (*Acacia mellifera, A.reficiens, A. tortilis,* and *Dichrostachys cinerea*). Specifically, we wanted to know if cutting top shoots leads to a morphological plant response and to subsequent consequences for livestock. In the second project, we investigated the impact of debushing activities on the distribution of large herbivores on a farm level. In this study, we wanted to explore whether the distribution of different large herbivores (browser and grazer) is related to the different management of sites (e.g., to the different degrees of bush-encroached areas). In the following, we present extended summaries of both projects.

Understanding the influence of damage on bush encroacher seedlings

Introduction

Why is it important? - Intense interventions, e.g. clearing by mechanical cutting, the use of bulldozers, and the use of arboricides are commonly employed to address the problem of bush encroachment once shrubs have reached a size large enough to use these methods. In contrast, an intervention at an early life stage of the plants seems to be much more reasonable and cost effective. Joubert et al. (2014) developed a management expert system for arid and semi-arid savanna ecosystems in order to manage this problem. The proposed management interventions in these systems include pulling out seedlings and saplings, mowing, grazing and browsing, and the use of fire in the early stages of seedling development. In order to expand on these proposed interventions, we wanted to understand how early-stage seedlings of different bush encroacher species react to damage, e.g. by browsing or cutting.

Plants show multiple reactions to damage, and these reactions are specific to the damaged plant species. That is to say, not every plant might react with a defence strategy such as increasing thorniness (mechanical defence) or increasing plant defence (e.g. tannins; chemical strategy). There are examples where plants react with compensation to tissue loss, which leads to even higher attractiveness for herbivores (e.g. willows are known to react like this, Stolter, 2008). Regardless of the type of reaction to damage, it will have an impact on the subsequent herbivory.

In our study, we tested:

a) if different bush encroacher species react differently to damage of the top shoot. Here, we focused on morphological plant response; e.g., the development of larger thorns or multiple branching;
b) if different bush encroacher species show differences in mortality rate after cutting to the ground;
c) if plant response results in a reduction of utilisation for subsequently feeding livestock (e.g., goats and sheep).

Methods

In a greenhouse experiment (Fig. 1), four different plant species involved in bush encroachment (*Acacia mellifera* [*Senegalia mellifera*, blackthorn, swarthaak], *A. tortilis* [*Vachellia tortilis*, umbrella thorn acacia], *A. reficiencs* [*Vachellia reficiens*, red bark acacia, rooihak], and *Dichrostachy cinerea* [sicklebush]) were tested for their response to damage by cutting the upper top shoots of

Figure 1: Greenhouse experiment with different bush encroacher seedlings.

three-month-old seedlings. Three months after manipulation, we determined the morphological changes in the plants (e.g., the size of thorns). In the next step, we fed the plants, now about six months old, to female Cameroon blackbelly sheep and female boer goats in order to test for consequences on subsequent consumers. In this phase, we monitored 4-5 animals in 4-7 feeding trials (depending on availability of the plants) with red bark acacia, sicklebush, and blackthorn, using 14 plants in each trial in a random design. And in the last step, we cut all seedlings consistently to ground level immediately after the feeding trials and investigated the survival/mortality rate in the following months. The latter was done to understand the influence of ground cutting (e.g., mowing) on seedlings.

Results

All investigated species reacted with changes in morphology to the damage of the top shoots, e.g., by building larger thorns (mean values for 40 sicklebush specimens: 9.74 mm for treated plants; 3.95 mm for control plants). We found that damage to the top shoot of acacia species led to an increase in branching and the loss of a leader shoot; this was most evident for blackthorn (mean: 4.52 side branches per treated plant vs. 2.60 side branches per control plant, Fig. 2). In particular, red bark acacia and umbrella thorn acacia more often grew a substitute top shoot and continued to grow normally (mean of 20 red bark acacia: 2.73 side branches per treated plant). Sicklebush started to build adventive (additional) ground shoots after cutting the top shoot (2 of 20 specimens), which can be seen as a sort of asexual reproduction (Fig. 3).

Additionally, we tested the survival rate after cutting. Severe cuttings, in which the seedlings (*A. mellifera*, *A. reficiens,* and *D. cinerea*) were cut down to ground level, resulted in the highest survival rates for *A. reficiens* (red bark acacia, roihak; over 90% of the seedling showed a vigorous resprout), while *A. mellifera* (blackthorn) survived with 50% and less than 8% of the *D. cinerea* (sicklebush) seedlings survived the severe ground cutting.

From the results of the damage experiment, we expected differences in palatability between damaged plants and control plants. Interestingly, goat browsing was unaffected by either thorn size or number, nor was it affected by differences in chemical composition (for changes in plant chemistry, see Stolter et al., 2018 in this volume). Interestingly, sicklebush was favoured over the other encroacher species (mean biomass eaten: 42% of red bark acacia and 32% of blackthorn) by goats, despite its enormous (but softer) spines, and was eaten almost down to the ground (mean biomass eaten: 90%). In contrast, sheep totally refused to feed on any of the species offered, no matter if it was a treated plant or a control plant. (More detailed results will be published by Stolter & Joubert elsewhere).

Synthesis and outlook

All the tested encroacher species reacted to top shoot damage. In particular, blackthorn reacted to the loss of the top shoot with increased, enhanced branching (e.g., more side branches, no substitute leader shoot). Browsing and other damage to blackthorn seedlings would likely result in exacerbating the problem of bush encroachment by promoting an increasingly multi-stemmed individual which is more difficult to control at a

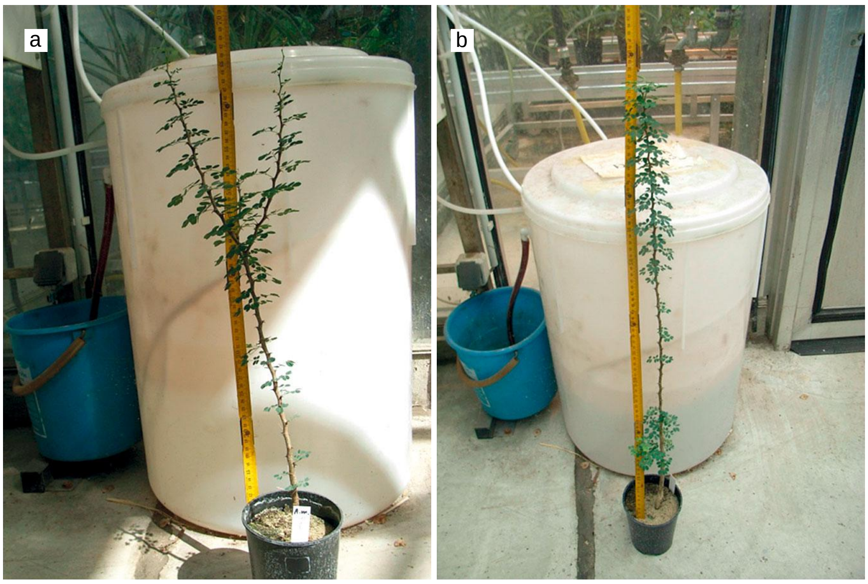


Figure 2: Plant response three months after top shoot damage: (a) blackthorn seedling showing multiple branching after cutting the top shoot; (b) totally undisturbed control plant (blackthorn) with one leader shoot (top shoot).

Figure 3: Sicklebush developed additional ground shoots after cutting the top shoot.

later stage. Bearing in mind that the survival rate of blackthorn was about 50% after ground-cutting, the results imply that any intervention would have to start at a much earlier stage after germination, e.g., when seedling are only a few centimetres high. Browsing by many different ground-feeding herbivores (e.g. goats, oryx, and hares) might be effective to reduce plant recruitment. Hares have been shown to have a significant impact on blackthorn seedling survival (Joubert et al., 2011). Blackthorn leaves are very nutritious, with the highest protein content of all four species (Stolter et al., 2018, in this volume), and the species is thus potentially beneficial for game and livestock. However, the small but very hard and hooked thorns are an effective defence against browsing in later growing stages, which might lead to a lower acceptance of this species (e.g., by Cameroon blackbelly sheep in our experiment, Fig. 4), especially when plants are of a certain height and multi-stemmed. In contrast to blackthorn, the development of multiple branched individuals was less pronounced in red bark acacia *(A. reficiens)*, but the survival rate of this species was very high. Therefore, we assume that ground cutting or grazing of this species might only be effective in combination with pulling out seedlings for control. Sicklebush showed also less branching in comparison with blackthorn, but reacted with the development of large, but softer thorns on the side branches. When only cut at the first centimetres of the top shoot, plants sometimes developed adventive shoots. This might lead to an increasing number of plants after damage occurs. In contrast to the other investigated plant species, sicklebush might only have a low survival rate when cut or fed down to the ground level.

The post-damage changes, especially in morphology, might lead to differences in attractiveness between damaged and undamaged plants for subsequent herbivores. Furthermore, different herbivores might react differently to morphological defences such as thorns, as our results from the feeding trial show. In our test, the sheep breed (Cameroon blackbelly, Fig. 4) did not feed on any of the offered plants; this might disqualify them for any management purposes in this respect. However, we have to admit that the diet of neither sheep nor goats was restricted; therefore, food choice in a harsh environment, with fewer feeding opportunities, might lead to the acceptance of these plants by Cameroon blackbelly. In contrast, the chosen boer goats were not concerned about lower plant nutritional quality or enhanced morphological plant defence (such as thorns) and fed on all bush encroacher seedlings (Fig. 4, 5). Interestingly, there was a strong preference for sicklebush, resulting in an almost total loss of the above-ground plant material. In combination with the low survival rate of sicklebush, goats (under controlled conditions) might be a 'natural option' to effectively decrease sicklebush seedling populations.

Figure 4: (a) Cameroon blackbelly sheep and, (b) boer goats (in the experimental setup). Bush encroacher seedlings were offered to several animals for several days. Sheep refused to feed on the seedlings.

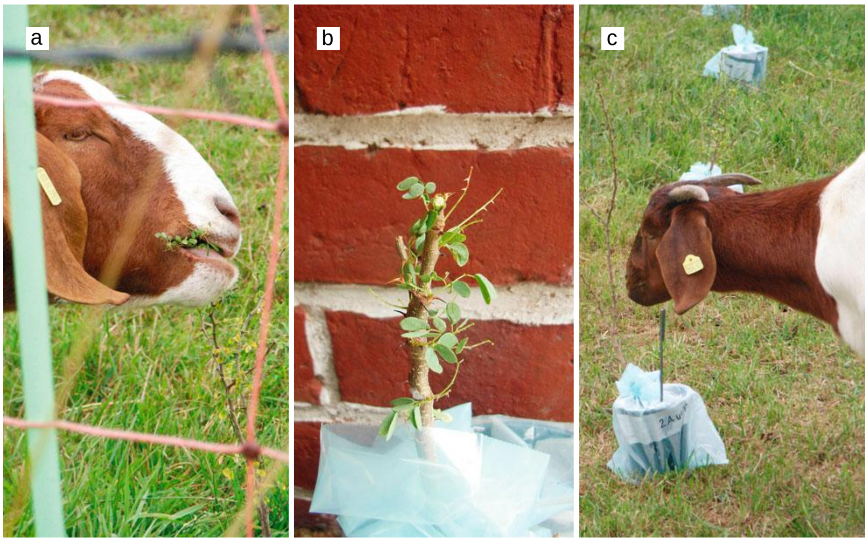


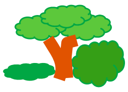
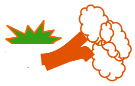
Figure 5: (a) Boer goat feeding on blackthorn, (b) stem feeding on blackthorn and, (c) leaf stripping on red bark acacia by goats.

Impacts of bush encroachment management on large herbivore distribution

Introduction

Why is it important? - Different management strategies have been developed to deal with bush-encroached areas (e.g., Joubert et al., 2014). In particular, the removal of woody plants, so-called bush clearing, combined with reseeding with perennial grasses is a frequently used, cost-effective strategy (Smit, 2004). At the same time, the removal of large amounts of bushes and shrubs in the savanna ecosystem might influence ecosystem processes and function with impacts on factors ranging from soils to large herbivore communities (e.g., Buyer & Maul,

Table 1. Summary of the results of habitat utilization in relation to different management types on a farm in Namibia. HC = Height classes: small: <51cm (HC1), medium: 51-180cm (HC2), tall: >180cm (HC3).

	Site			
	A	B	C	D
Intervention type	None	Bulldozer cleared in 2010	Stump-burned in 2010	None
Regeneration management etc.		Buffalo grass (*Cenchrus ciliaris*) seeded, grazed by cattle in 2013	Dead wood not removed, grass mixture was seeded	
Results: vegetation characteristics	Lowest grass cover, highest thornbush cover (all height classes).	Highest grass cover, lowest occurrence of height class HC2 and 3.	Lowest thornbush cover, low occurrence of HC2	High occurrence of HC2 but low occurrence of HC3
				
Habitat utilisation				

2016). Therefore, it is vital to understand these influences of bush clearing in order to develop sustainable management strategies likely to result in the maintenance of savannas' capacity to deliver ecosystem services and functions in the long term. In this context, the influence of bush clearing on the habitat utilisation of different large herbivores is both evident and important.

Large herbivores are of high importance not only for ecosystem processes but also for humans, e.g., as a food resource (livestock, game, and bush meat) and as flagships for tourism and nature conservation. The re-transformation of encroached sites will enhance carrying capacity for livestock and free-ranging grazers, but it will also result in a better visibility for large wild herbivores, which is important for tourism and countability for management purposes (for example, for conservation issues). On the other hand, bushes and dense vegetation offer food resources for browsers and the possibility for shelter (see also Joubert et al., 2018 in this volume)

In this regard, we wanted to know which vegetation factor (e.g., thornbush number, thornbush cover, tree heights, grass cover) determines the habitat utilisation (measured via faecal pellet counts) of two typical grazers (warthog, gemsbok) and one browser (greater kudu). Several studies have dealt with the distribution of grazers and browsers (e.g. Rodgers, 1984; Knight, 1991; Dekker et al., 1996; Valeix et al., 2011). Due to their results, we expected that typical grazers would prefer the open bush-cleared areas, while typical browsers should prefer non-cleared sites. For example, we wanted to know, if a typical grazer is always found in an open area and if grass cover is the "driver" for this.

Methods

On a private cattle farm, we chose four sites differing in bush encroachment management (for details, see Schwarz et al., 2017). Grass cover, thornbush cover, and the abundance of different thornbush species (e.g., *Acacia mellifera* [blackthorn], *Dichrostachys cinera* [sicklebush]) was determined, and those species were additionally grouped into height classes (HC) (small: < 51 cm [HC1]; medium: 51-180 cm [HC2]; tall: > 180 cm [HC3]). The habitat use of greater kudu (*Tragelaphus strepsiceros*), gemsbok (*Oryx gazella*), and common warthog (*Phacochoerus africanus*) were determined using faecal pellet counts (see also Joubert et al., 2018 for this method). Two sites were not subjected to bush clearing (see Tab. 1, sites A, D). One site was cleared by stump burning and reseeded with a grass mixture (site C); the other site was cleared by bulldozers and reseeded with blue buffalo grass (buffel grass, *Cenchrus cilliaris,* site B). The impact of bush encroachment management was clearly mirrored by differences in vegetation structure and composition determined by a vegetation survey (Schwarz et al., 2017). Sites A and D (no intervention) had the highest thornbush cover (A: 15.5%, D: 13.5%) but differed in number of small bushes (A mean number: 26, mean height: 24.3 cm; D mean number: 10, mean height 65.8 cm). Sites B and C had similar low thornbush cover and number (mean cover B: 5.83%; C: 4.33%; mean number for both sites: 9), but differed in mean thornbush height (B: 86.44 cm, C: 35.30 cm) and grass cover was highest on site B (33.75%). The influence of different vegetation parameters (e.g., thornbush and grass cover, height classes of bushes, thornbush number) on herbivore habitat utilisation was calculated using generalised linear models (detailed results are presented in Schwarz et al., 2017).

Results

In line with our expectations, the results of our model show a strong relationship between greater kudu and the occurrence of thorn bushes of medium size, which were mainly found at site D (highest mean faecal pellet counts for greater kudu: 1.8 at site D), but greater kudu were also found on the site with the lowest thornbush cover (see Tab. 1, sites C, D) but virtually absent at site A. We found warthog using the same site as cattle, which was an open site with only a few trees, reseeded with blue buffalo grass after bush clearing (see Tab. 1, site B, highest mean faecal pellet counts: 13.7) and our models revealed the impact of grass cover and high trees (HC 3) on warthog distribution. But against expectation, gemsbok did not share this open, bush-cleared site. Instead, gemsbok preferred a non-cleared site relatively high in thornbush cover of medium height (Tab. 1, site A). Faecal pellet counts were highest at sites A and C (mean A: 5.5; C: 3.3) and lowest at B and D (B: 0.4 ; D: 0.8). Accordingly, we gained the best models by including thornbushes of height class 2 in our models for gemsbok habitat utilisation. More detailed results are found in Schwarz et al. (2017).

Synthesis and Outlook

Every manipulation of ecosystems results in changes of the habitat with effects on vegetation composition and subsequent consequences for habitat use and movements of animals (e.g., Cogger & Cogger, 2003; Archibald et al., 2005; Haussmann et al., 2016). Changes in the natural herbivore composition are ascribed as one driver of the development of bush encroachment (e.g., Staver et al., 2009). Therefore, it is necessary to understand the habitat utilisation of wild free-ranging herbivores and the interaction between species. Our study (Schwarz et al., 2017) is a case study. Therefore, it might be interesting to investigate some of our assumptions further in the future. The site most preferred by greater kudu was covered with bushes of medium height, which is the most favourable browsing height for this species (Dutoit, 1990; de Garine-Wichatitsky et al., 2004). If we assume a high greater kudu population density, bushes might be kept at this height, especially if plant response to browsing promotes further rebrowsing e.g., by enhanced plant quality (Stolter, 2008) or plants react to browsing by building more branches, resulting in many multiple-stemmed plants with large thorns as described in the project above, upon which only specialised herbivores will feed. Therefore, the feeding behaviour of herbivores and the responses of plants are important for future research in order to understand and manage bush-encroached sites.

We found the most warthog faecal pellets on a site reseeded with blue buffalo grass, which might not be an optimal feed for warthog, as it is a tall grass species. However, plants react to feeding damage, and some species are known to facilitate a higher quality for subsequent consumers resulting in a positive feedback loop (McNaughton et al., 1983; Stolter, 2008). We assume that due to their feeding activity, cattle might create grazing lawns, resulting in an optimal feeding height and possibly higher food quality for ground-feeding herbivores like warthog (Arsenault & Owen-Smith, 2002; Treydte et al., 2006).

In contrast, gemsbok did not utilise this reseeded bush-cleared area. We assume that either competition (e.g., between gemsbok and cattle, warthog) and/or risk avoidance (e.g., due to hunting pressure, Benhaiem et al., 2008) might lead to the utilisation of another site by gemsbok, as gemsbok are frequently hunted on the farm and the non-cleared site was mainly used by gemsbok calves (Schwarz et al., 2017). Supposing that hunting was the reason for the distribution of gemsbok, bush clearing in connection with hunting might foil the aim of gaining better visibility of the animals for tourists or management purposes (e.g., counting). Furthermore, the utilisation of the non-cleared area by gemsbok might offer different food plants without competing with cattle or warthog. Due to adaptations to seasonal changes in vegetation, gemsbok are able to use dicotyledonous plants, e.g. Leucosphaera bainesii, during the dry season (e.g., Gagnon & Chew, 2000; Bothma et al., 2002; Schwarz, 2015, who determined food selection of gemsbok on this farm by investigating faecal pellets and rumen content). Therefore, the use of the non-cleared area might not only be beneficial in terms of risk avoidance but also from the nutritional perspective of the animal. We propose that habitat heterogeneity (bush-cleared sites next to sites with higher bush abundance) might be beneficial for the maintenance of a high diversity in habitat utilisation of large herbivores.

Conclusion

Our experiments on bush encroacher seedlings of the thornbush savanna demonstrate that early intervention in a seedling stage might be a useful tool to reduce bush encroachment. However, we found that different plant species reacted differently to damage of the top shoot and showed pronounced differences in survival rate. Thus, a species-specific management plan with species-specific timing of intervention is necessary to gain optimal results. This is important, as different savanna ecosystems are invaded by different bush encroacher species. Knowledge about plant species response is essential, as inappropriate procedures might exacerbate the problem of bush encroachment (e.g., creating multi-stem individuals, enhancing asexual reproduction). Ground-feeding herbivores with a wide dietary niche such as controlled goats and wild herbivores (e.g., hares, gemsbok, eland, stenbok) seem to be beneficial for reducing plant recruitment in most cases. But also in this case, food choice is species-specific. Hence, we need more studies to understand plant response and diet selection of herbivores to be able to control undesirable vegetation changes in future.

We found clear effects of different bush-clearing methods on vegetation structure and composition, which was subsequently reflected in the habitat utilisation of wild herbivores. However, some of our findings were unexpected and can only be explained by other factors (e.g., hunting or food competition). To maintain biodiversity and to ensure the coexistence of humans, cattle, and wildlife, it is essential to create a heterogeneous environment in which different requirements (e.g., for food, resting, shelter) can be satisfied. Still, we need more knowledge to understand the drivers of habitat utilisation for many wildlife species to enable optimal management in a changing world.

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References

Archer, S., Schimel, D.S. & Holland, E.A. (1995) Mechanisms of shrubland expansion: land use, climate or CO_2? *Climatic Change*, **29**, 91–99.

Archibald, S., Bond, W., Stock, W. & Fairbanks, D. (2005) Shaping the landscape: Fire–grazer interactions in an African savanna. *Ecological applications*, **15**, 96–109.

Arsenault, R. & Owen-Smith, N. (2002) Facilitation versus competition in grazing herbivore assemblages. *Oikos*, **97**, 313–318.

Benhaiem, S., Delon, M., Lourtet, B., Cargnelutti, B., Aulagnier, S., Hewison, A.M., Morellet, N. & Verheyden, H. (2008) Hunting increases vigilance levels in roe deer and modifies feeding site selection. *Animal Behaviour*, **76**, 611–618.

Bond, W.J. (2008) What limits trees in C4 grasslands and savannas? *Annual Review of Ecology, Evolution, and Systematics*, **39**, 641–659.

Bothma, J.d.P., Van Rooyen, N. & Du Toit, J. (2002) Antelope and other smaller herbivores. *Bothma, J. Du P.(ed.)*, 149–175.

Buyer, J.S. & Maul, J.E. (2016) Soil microbial communities following bush removal in a Namibian savanna. *Soil*, **2**, 101.

Cogger, H.G. & Cogger, H.G. (2003) *Impacts of land clearing on Australian wildlife in Queensland*. World Wide Fund for Nature Australia, Brisbane.

de Garine-Wichatitsky, M., Fritz, H., Gordon, I.J. & Illius, A.W. (2004) Bush selection along foraging pathways by sympatric impala and greater kudu. *Oecologia*, **141**, 66–75.

De Klerk, J. (2004) *Bush Encroachment in Namibia: Report on Phase 1 of the Bush Encroachment Research, Monitoring, and Management Project*. Ministry of Environment and Tourism, Directorate of Environmental Affairs, Windhoek.

Dekker, B., Van Rooyen, N. & Bothma, J.d.P. (1996) Habitat partitioning by ungulates on a game ranch in the Mopani veld. *South African Journal of Wildlife Research*, **26**, 117–122.

de Wet, M.J. (2015) Harvesting of encroacher bush: Compendium of harvesting technologies for encroacher bush in Namibia. Ministry of Agriculture, Water, and Forestry/ Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Windhoek.

Dutoit, J. (1990) Feeding-height stratification among African browsing ruminants. *African Journal of Ecology*, **28**, 55–61.

Fynn, R.W., Augustine, D.J., Peel, M.J. & Garine-Wichatitsky, M. (2016) Strategic management of livestock to improve biodiversity conservation in African savannas: A conceptual basis for wildlife–livestock coexistence. *Journal of Applied Ecology*, **53**, 388–397.

Gagnon, M. & Chew, A.E. (2000) Dietary preferences in extant African Bovidae. *Journal of Mammalogy*, **81**, 490–511.

Graz, P.F. (2008) The woody weed encroachment puzzle: Gathering pieces. *Ecohydrology*, **1**, 340–348.

Haussmann, N.S., Kalwij, J.M. & Bezuidenhout, S. (2016) Some ecological side-effects of chemical and physical bush clearing in a southern African rangeland ecosystem. *South African Journal of Botany*, **102**, 234–239.

Joubert, D., Rothauge, A. & Smit, G. (2008) A conceptual model of vegetation dynamics in the semi-arid highland savanna of Namibia, with particular reference to bush thickening by *Acacia mellifera*. *Journal of Arid environments*, **72**, 2201–2210.

Joubert, D.F., Smit, G.N. Johannes, M. & Sikongo, I.(2011) Do hares help to keep semi-arid savannas open? Preliminary evidence suggests they do. *Proceedings of the IX International Rangeland Congress*. Rosario, Argentina, 2–8 April, 2011.

Joubert, D., Zimmermann, I., Fendler, J., Winschiers-Theophilus, H., Graz, F.P., Smit, N. & Hoffman, M.T. (2014) The development of an expert system for arid rangeland management in central Namibia with emphasis on bush thickening. *African Journal of Range and Forage Science*, **31**, 161–172.

Joubert, D. F., Stolter, C., Krewenka, K. M., Uunona, N., Amputu, V., Nghalipo, E., Thompson, S., Schütte, K., Kruspe, M., Throop, H., du Preez, P., Beytell, P., le Roux, M. & Aindongo, H. (2018) Impacts of fire history in a semi-arid woodland savanna. This volume.

Knight, M. H. (1991) Ecology of the gemsbok *Oryx gazella gazella* (Linnaeus) and blue wildebeest *Connochaetes taurinus* (Burchell) in the southern Kalahari. Doctoral thesis, University of Pretoria, Pretoria.

Lange, G.M., Barnes, J.I. & Motinga, D.J. (1998) Cattle numbers, biomass, productivity, and land degradation in the commercial farming sector of Namibia, 1915-95. *Development Southern Africa*, **15**, 555–572.

Lehmann, C.E.R., Ratnam, J. & Hutley, L.B. (2009) Which of these continents is not like the other? Comparisons of tropical savanna systems: key questions and challenges. *New Phytologist*, **181**, 508–511.

McNaughton, S., Wallace, L.L. & Coughenour, M.B. (1983) Plant adaptation in an ecosystem context: effects of defoliation, nitrogen, and water on growth of an African C4 sedge. *Ecology*, **64**, 307–318.

O'Connor, T.G., Puttick, J.R. & Hoffman, M.T. (2014) Bush encroachment in southern Africa: Changes and causes. *African Journal of Range and Forage Science*, **31**, 67–88.

Rodgers, W. (1984) Warthog ecology in south-east Tanzania. *Mammalia*, **48**, 327–350.

Scholes, R. & Archer, S. (1997) Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics*, **28**, 517–544.

Schwarz, K. (2015) Bush encroachment and herbivore distribution in the Namibian thornbush savanna. Master's thesis, University of Hamburg, Hamburg.

Schwarz, K., Finckh, M. & Stolter, C. (2017) Influence of differently managed bush-encroached sites on the large herbivore distribution in the Namibian savanna. *African Journal of Ecology,* 1–11.

Skarpe, C. (1990) Shrub layer dynamics under different herbivore densities in an arid savanna, Botswana. *Journal of Applied Ecology*, **27**, 873–885.

Smit, G. (2004) An approach to tree thinning to structure southern African savannas for long-term restoration from bush encroachment. *Journal of Environmental Management*, **71**, 179–191.

Staver, A.C., Bond, W.J., Stock, W.D., Van Rensburg, S.J. & Waldram, M.S. (2009) Browsing and fire interact to suppress tree density in an African savanna. *Ecological Applications*, **19**, 1909–1919.

Stevens, N., Lehmann, C.E., Murphy, B.P. & Durigan, G. (2017) Savanna woody encroachment is widespread across three continents. *Global Change Biology*, **23**, 235–244.

Stolter, C. (2008) Intra-individual plant response to moose browsing: Feedback loops and impacts on mulitple consumers. *Ecological Monographs*, **78**, 167–183.

Stolter, C., Ramoelo, A., Kesch, K., Madibela, O., Cho, M.A. & Joubert, D.F. (2018) Forage quality and availability for large herbivores in southern African rangelands. This volume.

Treydte, A.C., Bernasconi, S.M., Kreuzer, M. & Edwards, P.J. (2006) Diet of the common warthog (*Phacochoerus africanus*) on former cattle grounds in a Tanzanian savanna. *Journal of Mammalogy*, **87**, 889–898.

Valeix, M., Fritz, H., Sabatier, R., Murindagomo, F., Cumming, D. & Duncan, P. (2011) Elephant-induced structural changes in the vegetation and habitat selection by large herbivores in an African savanna. *Biological Conservation*, **144**, 902–912.

Ward, D. (2005) Do we understand the causes of bush encroachment in African savannas? *African Journal of Range and Forage Science*, **22**, 101–105.

References [CrossRef]

Archer, S., Schimel, D.S. & Holland, E.A. (1995) Mechanisms of shrubland expansion: land use, climate or CO_2? *Climatic Change*, **29**, 91–99. CrossRef

Archibald, S., Bond, W., Stock, W. & Fairbanks, D. (2005) Shaping the landscape: Fire–grazer interactions in an African savanna. *Ecological applications*, **15**, 96–109. CrossRef

Arsenault, R. & Owen-Smith, N. (2002) Facilitation versus competition in grazing herbivore assemblages. *Oikos*, **97**, 313–318. CrossRef

Benhaiem, S., Delon, M., Lourtet, B., Cargnelutti, B., Aulagnier, S., Hewison, A.M., Morellet, N. & Verheyden, H. (2008) Hunting increases vigilance levels in roe deer and modifies feeding site selection. *Animal Behaviour*, **76**, 611–618. CrossRef

Bond, W.J. (2008) What limits trees in C4 grasslands and savannas? *Annual Review of Ecology, Evolution, and Systematics*, **39**, 641–659. CrossRef

Bothma, J.d.P., Van Rooyen, N. & Du Toit, J. (2002) Antelope and other smaller herbivores. *Bothma, J. Du P.(ed.)*, 149–175.

Buyer, J.S. & Maul, J.E. (2016) Soil microbial communities following bush removal in a Namibian savanna. *Soil*, **2**, 101. CrossRef

Cogger, H.G. & Cogger, H.G. (2003) *Impacts of land clearing on Australian wildlife in Queensland*. World Wide Fund for Nature Australia, Brisbane.

de Garine-Wichatitsky, M., Fritz, H., Gordon, I.J. & Illius, A.W. (2004) Bush selection along foraging pathways by sympatric impala and greater kudu. *Oecologia*, **141**, 66–75. CrossRef

De Klerk, J. (2004) *Bush Encroachment in Namibia: Report on Phase 1 of the Bush Encroachment Research, Monitoring, and Management Project*. Ministry of Environment and Tourism, Directorate of Environmental Affairs, Windhoek.

Dekker, B., Van Rooyen, N. & Bothma, J.d.P. (1996) Habitat partitioning by ungulates on a game ranch in the Mopani veld. *South African Journal of Wildlife Research*, **26**, 117–122.

de Wet, M.J. (2015) Harvesting of encroacher bush: Compendium of harvesting technologies for encroacher bush in Namibia. Ministry of Agriculture, Water, and Forestry/ Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Windhoek.

Dutoit, J. (1990) Feeding-height stratification among African browsing ruminants. *African Journal of Ecology*, **28**, 55–61. CrossRef

Fynn, R.W., Augustine, D.J., Peel, M.J. & Garine-Wichatitsky, M. (2016) Strategic management of livestock to improve biodiversity conservation in African savannas: A conceptual basis for wildlife–livestock coexistence. *Journal of Applied Ecology*, **53**, 388–397. CrossRef

Gagnon, M. & Chew, A.E. (2000) Dietary preferences in extant African Bovidae. *Journal of Mammalogy*, **81**, 490–511. CrossRef

Graz, P.F. (2008) The woody weed encroachment puzzle: Gathering pieces. *Ecohydrology*, **1**, 340–348. CrossRef

Haussmann, N.S., Kalwij, J.M. & Bezuidenhout, S. (2016) Some ecological side-effects of chemical and physical bush clearing in a southern African rangeland ecosystem. *South African Journal of Botany*, **102**, 234–239. CrossRef

Joubert, D., Rothauge, A. & Smit, G. (2008) A conceptual model of vegetation dynamics in the semi-arid highland savanna of Namibia, with particular reference to bush thickening by *Acacia mellifera*. *Journal of Arid environments*, **72**, 2201–2210. CrossRef

Joubert, D.F., Smit, G.N. Johannes, M. & Sikongo, I.(2011) Do hares help to keep semi-arid savannas open? Preliminary evidence suggests they do. *Proceedings of the IX International Rangeland Congress*. Rosario, Argentina, 2–8 April, 2011.

Joubert, D., Zimmermann, I., Fendler, J., Winschiers-Theophilus, H., Graz, F.P., Smit, N. & Hoffman, M.T. (2014) The development of an expert system for arid rangeland management in central Namibia with emphasis on bush thickening. *African Journal of Range and Forage Science*, **31**, 161–172. CrossRef

Joubert, D. F., Stolter, C., Krewenka, K. M., Uunona, N., Amputu, V., Nghalipo, E., Thompson, S., Schütte, K., Kruspe, M., Throop, H., du Preez, P., Beytell, P., le Roux, M. & Aindongo, H. (2018) Impacts of fire history in a semi-arid woodland savanna. This volume. CrossRef

Knight, M. H. (1991) Ecology of the gemsbok *Oryx gazella gazella* (Linnaeus) and blue wildebeest *Connochaetes taurinus* (Burchell) in the southern Kalahari. Doctoral thesis, University of Pretoria, Pretoria.

Lange, G.M., Barnes, J.I. & Motinga, D.J. (1998) Cattle numbers, biomass, productivity, and land degradation in the commercial farming sector of Namibia, 1915-95. *Development Southern Africa*, **15**, 555–572. CrossRef

Lehmann, C.E.R., Ratnam, J. & Hutley, L.B. (2009) Which of these continents is not like the other? Comparisons of tropical savanna systems: key questions and challenges. *New Phytologist*, **181**, 508–511. CrossRef

McNaughton, S., Wallace, L.L. & Coughenour, M.B. (1983) Plant adaptation in an ecosystem context: effects of defoliation, nitrogen, and water on growth of an African C4 sedge. *Ecology*, **64**, 307–318. CrossRef

O'Connor, T.G., Puttick, J.R. & Hoffman, M.T. (2014) Bush encroachment in southern Africa: Changes and causes. *African Journal of Range and Forage Science*, **31**, 67–88. CrossRef

Rodgers, W. (1984) Warthog ecology in southeast Tanzania. *Mammalia*, **48**, 327–350. CrossRef

Scholes, R. & Archer, S. (1997) Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics*, **28**, 517–544. CrossRef

Schwarz, K. (2015) Bush encroachment and herbivore distribution in the Namibian thornbush savanna. Master's thesis, University of Hamburg, Hamburg.

Schwarz, K., Finckh, M. & Stolter, C. (2017) Influence of differently managed bush-encroached sites on the large herbivore distribution in the Namibian savanna. *African Journal of Ecology*, 1–11.

Skarpe, C. (1990) Shrub layer dynamics under different herbivore densities in an arid savanna, Botswana. *Journal of Applied Ecology*, **27**, 873–885. CrossRef

Smit, G. (2004) An approach to tree thinning to structure southern African savannas for long-term restoration from bush encroachment. *Journal of Environmental Management*, **71**, 179–191. CrossRef

Staver, A.C., Bond, W.J., Stock, W.D., Van Rensburg, S.J. & Waldram, M.S. (2009) Browsing and fire interact to suppress tree density in an African savanna. *Ecological Applications*, **19**, 1909–1919. CrossRef

Stevens, N., Lehmann, C.E., Murphy, B.P. & Durigan, G. (2017) Savanna woody encroachment is widespread across three continents. *Global Change Biology*, **23**, 235–244. CrossRef

Stolter, C. (2008) Intra-individual plant response to moose browsing: Feedback loops and impacts on mulitple consumers. *Ecological Monographs*, **78**, 167–183. CrossRef

Stolter, C., Ramoelo, A., Kesch, K., Madibela, O., Cho, M.A. & Joubert, D.F. (2018) Forage quality and availability for large herbivores. This volume. CrossRef

Treydte, A.C., Bernasconi, S.M., Kreuzer, M. & Edwards, P.J. (2006) Diet of the common warthog (*Phacochoerus africanus*) on former cattle grounds in a Tanzanian savanna. *Journal of Mammalogy*, **87**, 889–898. CrossRef

Valeix, M., Fritz, H., Sabatier, R., Murindagomo, F., Cumming, D. & Duncan, P. (2011) Elephant-induced structural changes in the vegetation and habitat selection by large herbivores in an African savanna. *Biological Conservation*, **144**, 902–912. CrossRef

Ward, D. (2005) Do we understand the causes of bush encroachment in African savannas? *African Journal of Range and Forage Science*, **22**, 101–105. CrossRef

Rangelands

Initial experiments on intensified use of rangelands through enhanced water and nutrient cycling

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Abstract: Rangelands in southern Africa are degrading as human pressure on them increases. Better grazing management is clearly needed. Intensive management can also be applied to a few small areas, such as by harvesting rainwater to soak into the ground and support the growth of natural grasses and planted trees. Initial experiments were attempted at three sites by digging contour ditches, and in addition by constructing ponding banks at one of those sites. Earthmoving machinery was used at a 100 ha rural site, while contour ditches were manually dug with pick and spade at two small urban sites. Diverse tree species were planted below contour ditches for different functions and products, including 'chop-and-drop' mulching, tall protective canopies, and edible leaves, fruits, and pods. Much of the low rainfall experienced was soaked into the ground. However, the initial survival rates of tree seedlings was low, suggesting that tree planting should await some years to allow sufficient rainwater to be planted first. Useful lessons were learned from the various designs of infrastructure tried, which will be applied to further evolve appropriate regeneration methods. These must be integrated with other techniques that address the root causes of degradation, such as through the appropriate management of grazing and fires, while fitting into the heterogeneity occurring at different scales in the landscape.

Resumo: As pastagens do Sul de África estão a degradar-se enquanto a pressão humana aumenta. Uma melhor gestão do pastoreio é claramente necessária. A gestão intensiva pode também ser aplicada a algumas pequenas áreas, como ao colher a água da chuva para ensopar o solo e apoiar o crescimento de gramínias naturais e árvores plantadas. Experiências iniciais foram realizadas em três locais, com a escavação de valas de contorno e a construção de *ponding banks* num destes lugares. Maquinaria de terraplanagem foi utilizada num local rural de 100 ha, enquanto que as valas de contorno foram escavadas manualmente com picareta e pá em dois pequenos locais urbanos. Diversas espécies de árvores foram plantadas abaixo das valas de controno para diferentes funções e produtos, incluindo mulching *chop-and-drop*, copas de protecção altas, e folhas, frutos e vagens comestíveis. Grande parte da pouca chuva vivenciada infiltrou-se no solo. No entanto, as taxas iniciais de sobrevivência das plântulas de árvores foi baixa, sugerindo que a plantação deverá aguardar alguns anos para permitir primeiro a infiltração de água suficiente. Lições úteis foram retiradas dos vários projectos de infra-estruturas testados, as quais serão aplicadas para desenvolver futuros métodos de regeneração adequados. Estes devem ser integrados com outras técnicas que abordem as causas principais da degradação, como através da gestão adequada do pastoreio e dos fogos, ao mesmo tempo que se encaixam na heterogeneidade que ocorre em diferentes escalas na paisagem.

Introduction

Rangeland is defined by Craggs (2017) as land that provides grazing and foraging for livestock and wildlife, where the natural vegetation consists of native grasses, grass-like plants, flowering plants and shrubs, and introduced plant species that are naturalised. The Namibian rangelands of this study all receive a mean annual rainfall of approximately 350 mm, falling mostly during the single rainy season from December to April. The soil texture is mostly sandy loam with a gently sloping topography. The rangelands used to be savanna of perennial grassland with scattered bushes and trees of diverse species, but over the past decades they have become dominated by annual grasses and been encroached on by a few species of thorn bushes of the genera *Acacia* and *Dichrostachys* (de Klerk, 2004).

Some observers, including many Namibian farmers, believe that in the past, before inadvertent damage by modern humans, rangelands used to be highly productive. They supported abundant and diverse fauna and flora, behaving as a 'stepped diffusion hydroponic system' largely through self-reinforcing barriers on contour (Andrews, 2008) and seasonal migrations of animals (Fynn & Bonyongo, 2011), made possible by the heterogeneity of the landscape (Sianga et al., 2017). The process of rangeland degradation has been described by authors such as Ludwig & Tongway (1995) for the small scale; Milton et al. (1994) generally; and Pringle & Tinley (2003), Pringle et al. (2011), and Tinley & Pringle (2013b) for the broad scale. In sloping rangelands, gully incision and lowered base levels, often initiated by animal tracks, result in a downward spiral of desiccation and lowered fertility as water, organic debris, and soil flow out of the landscape (Pringle & Tinley, 2003). The common theme, regardless of the scale at which degradation occurs, is less efficient use of raindrops because of increased runoff and evaporation, while infiltration and transpiration decline.

There has been less documentation of rangeland degradation specific to Namibia. Over the past decades, most of Namibia's rangelands have degraded, as evidenced by symptoms such as lowered animal production and bush encroachment (de Klerk, 2004). Ward & Ngairorue (2000) measured the herbage standing crop on Namibian commercial farms along a rainfall gradient ranging in mean annual rainfall from 140 to 450 mm. They found that the herbage yield was approximately half that of 50 years previously, which they attribute to long-term heavy grazing. In addition, a large amount of soil and water has been lost, the fertility of the remaining soil has declined, and plant species composition has changed.

The greatest disruptions to nutrient cycling occurred through the sale of milk until the mid-1900s, and thereafter through sale of farm animals (Lau & Reiner, 1993) without farmers returning to the soil the minerals that the animals consumed by grazing year after year. In communal areas, the common practice of overnight kraaling of livestock also robs the land of minerals and organic matter, as much manure is deposited and confined to the kraals. In instances where it is recycled, the manure is not returned to the grazing land but instead to arable land and usually after much of its nitrogen and sulphur have been lost to the atmosphere as volatile gases. The few minerals returned to the rangeland through mineral licks and supplementary feed tend to focus on only a few elements such as phosphorous and sodium, thus failing to restore the balance of elements lost. The former practice of farmers supplying their animals with bonemeal has been declared illegal to comply with EU veterinary regulations (Kaurivi, 2013), and most Namibian and Botswanan bonemeal is now exported, as is most of the beef, together with all their minerals.

The degraded nutrient status of rangeland soil not only results in less nutritious grass but is also likely to contribute to bush encroachment (Mills et al., 2013). The encroached bushes are often blamed for degrading the rangeland, yet they are a symptom of the degradation and not its cause (Andrews, 2008). The increased bush growth can be viewed as nature's way of trying to regenerate a healthy soil by bringing up minerals through their deep roots (Sandhage-Hofmann et al., 2015) and increasing the soil's carbon content largely through growing roots that exude organic acids and sugars to feed beneficial soil microorganisms in return for minerals and organic nutrients (Bais et al., 2006). Large-scale clearing of bushes disrupts both water and nutrient cycles, leading to soil capping, increased runoff and evaporation, reduced organic matter, and lowered production from perennial vegetation.

Numerous approaches have been applied elsewhere using locally available materials to restore water and nutrient cycling. Critchley (1991) describes two projects in Burkina Faso. In the Agroforestry Project of Yatenga Province, farmers had built stone bunds at a slight gradient to divert runoff away from their fields. During successive years of drought, however, the project helped them shift these stone bunds to follow the contour to maximize infiltration and soil moisture availability for crops while building up organic matter from debris deposited upslope from the rocks. Where there were insufficient stones to adequately raise the bund height, a perennial grass, *Andropogon guyanus*, was planted on the upslope side of the stone line to serve the same filtering purpose. In the conservation and land development project known as Patecore in Kongoussi, many long, low permeable rock dams were constructed from loose stones and stretched across valley floors, thereby spreading floodwater and healing gullies. In Zimbabwe, the innovative water harvester Zephaniah Phiri developed ways to slow, spread, and sink runoff water in an integrated system of stone walls, pits, and ditches (Witoshynsky, 2000). Nevertheless, it took more than 15 years for these methods to be adopted by others, largely resulting from the negative attitude of extension workers who lacked faith in the locally developed technology (Murirwa et al., 2001). In Kenya, a high density of farmers allowed the intensive application of terracing, planting, and management of grazing to support their high population (Tiffen et al., 1994). The abundance of stone wall terraces of the Bakoni ruins in South Africa provide 'evidence of advanced technological and agricultural innovation, long before the colonial era' (Whitlock, 2015).

Methods

A few attempts were initiated to regenerate healthy water and mineral cycles on three small portions of Namibian rangeland (Fig. 1) by establishing contour ditches (Lancaster, 2013) for planting trees below them and by constructing ponding banks (Bastin et al., 2001) and bush filters aligned on contour to invigorate natural grasses at one of the sites. This was done on an experimental basis to learn from such action research

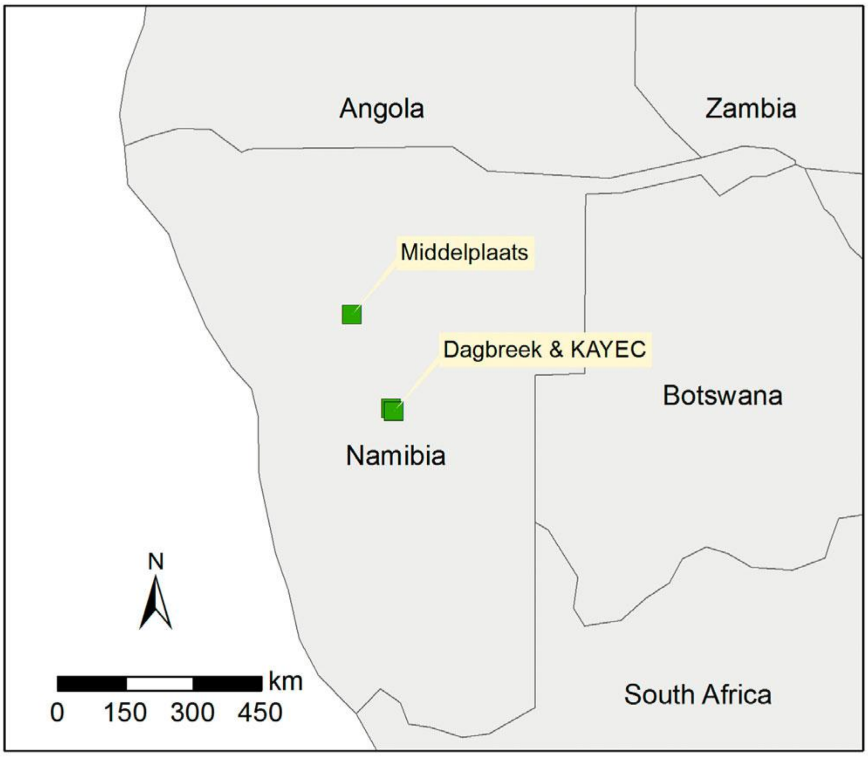

Figure 1: Location of the three sites where intensified use of rangelands was piloted.

for further application of successes and modification of partial failures.

Fruitful landscape at Farm Middelplaats

At Farm Middelplaats, approximately 40 km south-west of Otjiwarongo, evidence remains of rangeland degradation that has been taking place over past decades. Aligned patches of dark soil in slight depressions testify to former interconnected ephemeral wetlands. Dominance by annual grasses, with only a few remnant perennial grasses often on raised pedestals, bear testimony to the loss of water and soil in sheet flow, exacerbated by deep channelling of nearby ephemeral rivers. Overbrowsing by high densities of game animals that often visit the farm, such as oryx and red hartebeest, is evident on palatable woody species kept in a low coppiced state, except for a few mature individuals that previously escaped beyond browsing height.

On a 30 ha portion of the farm, 12 contour lines were marked out by laser or dumpy level in 2014 at 0.5 m height intervals. Two strips were bulldozed along the contour lines while avoiding large trees to leave them in place (Fig. 2), and a line was ripped (Fig. 3) for later keying in of soil heaped over it to form a bund (Stanton & Waterson, 2007). A grader was then used to dig a ditch along each contour line while heaping the dug soil on the downslope side over the rip line to form the bund. The combined depth of ditch and height of bund could hold water approximately 0.5 m deep to slowly infiltrate and moisten the soil below (Fig. 4). At each end of the ditch, the grader made an upward turn to hook the ditch and bund upwards by approximately 2 m to prevent water from spilling around the ends of the bund. The hook connected with a hump across the road (Fig. 5) in cases where it was considered worthwhile to divert water flowing down the road into the ditch, or from a ditch outside of the fruitful landscape to bring water across the road and into the ditch. Initially, spillways of 10 m width were made by removing soil from the top of the bund (Fig. 5), with the positions of spillways staggered between successive ditches, aimed at getting spilled water to zigzag its way down the landscape and increase infiltration time. In 2017, it was decided to install a second spilling ditch below each contour ditch, which would spread excess flow from spillways along the contour and then release it widely (Fig. 6), rather than as a concentrated release that then 'hit' the next contour ditch and bund downslope. We did this because it was felt the system was not accommodating major storm events effectively and that such events may increase in magnitude and frequency.

A variety of tree seedlings were planted below the ditches to provide different products and perform different functions (Leakey, 2014). These included large protective canopy trees with edible pods and deep roots, such as *Faidherbia albida* and *Acacia erioloba*; shorter thornless trees for 'chop-and-drop' mulching (Thurston, 1997), such as *Peltophorum africanum* and *Bolusanthus speciosus*; and trees that produce fruits, such as *Sclerocarya birrea* and *Berchemia discolor*, or edible leaves, such as *Moringa oleifera*. In 2017 two wires were added to the bottom of the fence around the 30 ha fruitful landscape to exclude large game animals.

Ponding banks at Farm Middelplaats

On another portion of Farm Middelplaats of approximately 50 ha, where bushes had previously been cleared and soil was therefore likely to be less fertile, locations were identified where water appeared to have been held back in the past, such as where the soil was darker in colour. Here contour lines were marked out for the bases of ponding banks, with gradients of approximately 1:200 to hook the bank upwards into an arm at each end to pond 10 to 20 cm of water. Care was taken to spill the water widely and slowly at one or both ends. Starting in 2015, but mostly in 2016, a bulldozer was used to construct the banks using two approaches. For banks receiving strong flows, soil was scraped from above the bank (Fig. 7), while for others it was scraped from below, which was further applied in 2017 (Fig. 8). For most banks, a powerful grader would have been far more cost effective than a bulldozer.

To construct several neighbouring ponding banks along the same contour, the contour line was marked out for approximately 80 m and then taken upwards by approximately 15 cm height over 30 m before being lowered again

Figure 2: Contour strips are cleared, except for large trees that are left in place.

Figure 3: A line is ripped where soil dug from the ditch will be heaped to key in the bund to better secure it with the ground below.

Figure 4: Water infiltrates in a contour ditch after a rain shower of 11 mm.

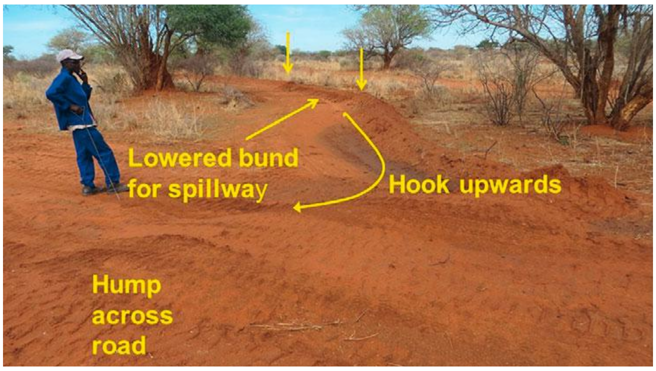

Figure 5: Upward hook to avoid spillage at end of ditch, and hump to divert water from road.

Figure 6: When grading a new ditch below the old contour ditch, the dug soil is heaped upslope so that water spilled from the upper ditch will first spread out to fill the lower ditch before spilling as wide sheet flow over the lower edge at ground level.

Figure 7: A ponding bank is built in September 2016 by scraping soil from above the bank.

Figure 8: A ponding bank is built in September 2017 by scraping soil from below the bank.

Figure 9: The bank is pushed down at its highest positions to allow spillover from ponding banks on each side to first fill the ditch below before excess water spills as wide sheet flow over the lower edge of the contour ditch.

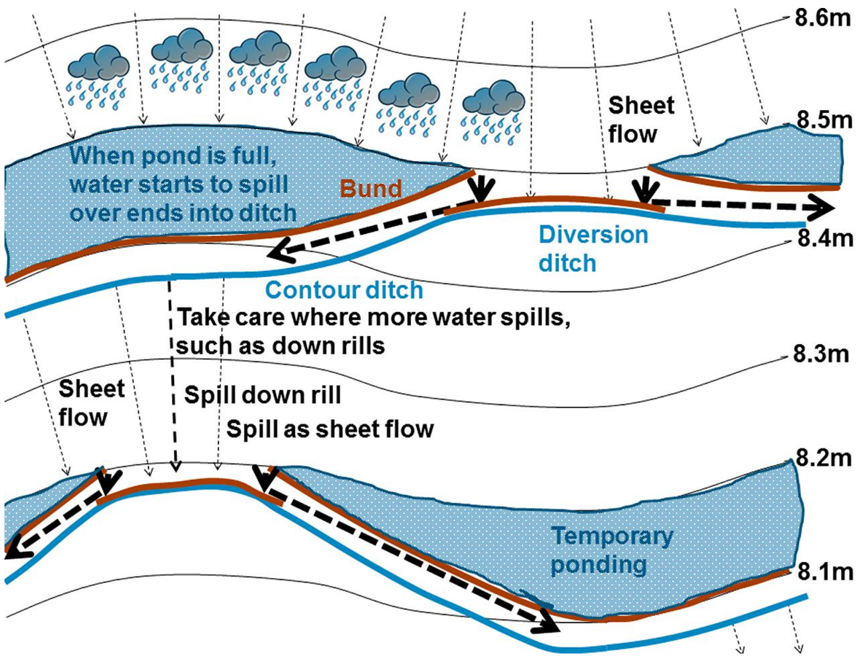

Figure 10: Sketch map to illustrate functioning of neighbouring ponding banks after rain.

over the next 30 m to rejoin the contour for another 80 m. After soil was bulldozed upwards along this wavy line, thereby digging a ditch below, the resulting bank was broken through from above (Fig. 9) and heaped below the ditch for water to spill from banks into the diversion ditch to flow into the contour sections of the ditches and later spill as sheet flow over the lower edge (Fig. 10). Deep ripping above and below the bank created a calming ‘sponge’ and prevented any tunnelling, respectively. Some wetland grass species were brought onto the farm and transplanted into the homestead garden for multiplication and eventual transplanting of propagules into the ponded areas above the banks.

Bush filter lines at Farm Middelplaats

On yet another portion of Farm Middelplaats of approximately 20 ha, two contour lines of several hundred metres each were marked out in 2016 and a longer one in 2017. Old grass seed was scattered along the lines and lightly raked in (Fig. 11) before being covered with branches cut from nearby thorn bushes with the cut stem facing downslope (Fig. 12). Different sections of these bush filters were experimentally constructed at two levels of intensity. The light filter comprised a single layer of medium-sized branches, while the dense filter had tightly packed small branches below medium-sized branches, followed by larger branches on top.

Urban fruitful landscapes in Windhoek

On a 2 ha portion of the campus of the Katutura Youth Enterprise Centre (KAYEC), four successive contour ditches were marked out and dug by NUST students using pick and spade between 2014 and 2016. Where each of the two lower ditches crossed a gully, a leaky weir was constructed with old tyres (Fig. 13) to divert most of the initial water flowing down the gully to the ditches on either side. A bund was heaped on the downslope side of three of the ditches, while soil from the other ditch was heaped to create a large diversion bund where water from the tar road outside the campus flowed in. This left the lower edge of the whole ditch of approximately 60 m length serving as the spillway.

In 2017 at the campus of Dagbreek School, the soil dug from a contour ditch of approximately 40 m was heaped to form a large bund across a shallow gully to divert its water into the ditch. At the other end, a pit was dug 1.5 m deep for organic material to be thrown in (Fig. 14) for improving fertility of spilled water.

Results

Fruitful landscape at Farm Middelplaats

Although the intention had been to let the seedlings depend entirely on rainwater and care for themselves with minimal input (Shepard, 2013), the 2014/2015 rainy season was very poor. This caused many of the planted tree seedlings to die, with only 17 seedlings surviving out of the 152 seedlings planted that season. Therefore, it was decided to irrigate surviving or newly planted seedlings with 1 L of water every 10 days unless sufficient rain had fallen. Another challenge was that many of the seedlings were browsed upon, especially in the dry season, by either wild or domestic animals. It took three years for sufficient soil moisture to accumulate below the contour ditches, as a result of which tree survival is expected to greatly improve.

By the end of the 2017 dry season, 315 planted tree saplings survived in the 30 ha fruitful landscape, mostly of *Moringa oleifera* (Fig. 15). More will be planted now that the surrounding fence has been strengthened by adding two wires and replacing some worn droppers and posts to keep out oryx and hartebeest, while horses are no longer allowed to graze there.

Spillage from contour ditches tended to occur as concentrated flow, either at designed spillways or at breaches through weak points in the bund. This required some maintenance work to repair bunds after intense rain and led to spreader ditches being dug in 2017 (Fig. 6).

Ponding banks at Farm Middelplaats

The 2017 rainy season resulted in a good vegetation response above the ponding banks (Fig. 16), where a dense cover of creeping legumes had established itself (Fig. 17). It was interesting to observe that the abundant wild melon plants were fruiting only where creeping legumes covered the soil underneath them. This was attributed (Hugh Lovel, Quantum Agriculture Consultancy, pers. comm.) to the organic acids exuded by legume roots releasing the tightly bound calcium-complexed minerals in the soil for uptake by both legumes and melons, to


Figure 11: Grass seed is scattered and lightly raked in along a contour line before being covered with thorn branches.


Figure 12: Branches are stacked to form a filter along the contour.


Figure 13: Old tyres are secured by steel posts to create a leaky weir.


Figure 14: Organic material is thrown into a pit at the end of a contour ditch to improve fertility of infiltrating water.


Figure 15: *Moringa oleifera* trees grow below a contour ditch.


Figure 16: View in April 2017 of the same ponding banks as in Figure 7.


Figure 17: Creeping legumes densely cover the ponded area above a bank.


Figure 18: Herbaceous plants establish under a bush filter line on contour.

Rangelands

Figure 19: Rainwater spills over a slightly lower edge of a contour ditch.

Figure 20: Denser grass grows where water spilled previously, thus trapping more sediment and puffing up soil underneath to achieve self-reinforcement.

later facilitate the establishment of more perennial grasses. At the end of the 2017 dry season, while most of the rangeland was dry, the perennial plants in and below the ponding banks were sprouting green growth, indicating the improved moisture stored in the soil.

Bush filter lines at Farm Middelplaats

Herbaceous plants established better under the dense filters (Fig. 18) than under the light filters, although forbs tended to dominate grasses. Termites started to consume many of the branches and animal paths crossed some of the light filters, as this portion of the farm was still exposed to high pressure from both wild animals and cattle.

Urban fruitful landscapes in Windhoek

Trees planted below the contour ditches initially established well, as the rocky soil allowed water to infiltrate deeply, and the lateral flow of water seems to have occurred rapidly, with good response from trees within one year of being planted.

However, the planted trees then faced the enormous challenge of vandalism by a minority of the hundreds of community members making use of the campus, mostly from the neighbouring school that had access to the soccer field on the KAYEC campus. Uprooted tree saplings were often found lying along the ditches.

The contour ditches with bunds on the lower side resulted in concentrated spillage that required some maintenance after intense rain. The contour ditch without a bund often filled with extra water from the tar road outside. The initial spillage took place over the slightly lower sections of the lower edge of this ditch (Fig. 19), resulting in denser grass growing in that moister soil (Fig. 20). This initiates self-reinforcement as used to occur in nature when the denser grass traps more sediment and puffs up the soil underneath because of the greater activity of soil organisms until water starts spilling more elsewhere, leading to a 'windscreen wiper' effect over the long term.

The fruitful landscape at Dagbreek was only started in 2017, but from the few rain showers that fell thereafter, it appeared that this setup was working well.

Discussion

Each of the different methods used for infiltrating more rainwater had its advantages and disadvantages, yet all appeared to be producing improved landscape functioning. They are addressing degradation processes of many decades, so none was expected to be a 'silver bullet'. All need to be integrated into a wider ecosystem management approach (Tinley & Pringle, 2013a). Therefore, despite setbacks, the true value of the works is not yet realised and the positive results are inspiring.

The ditches with bunds excavated from above could hold more water per volume of soil dug from them. However, the spilled water concentrating at their spillways or breached bunds tended to cause some erosion that required maintenance. The ditches without bunds started to show signs of self-reinforcement that would minimise maintenance requirements and lead to a more naturally stepped landscape. It is expected that the many contour ditches dug from below on Middelplaats in 2017 will allow wide spillage as sheet flow with such self-reinforcement properties.

Less earthmoving would be required for construction of a micro-catchment for each tree (Jo & Park, 2017). Although this may improve survival and growth rate of trees, it is unlikely to adequately control loss of rainwater as sheet flow. It may alternatively be possible to improve the establishment of trees by raising and planting them as long-stem tube-stock (Australian Plants Society, 2010), with their roots planted approximately 1 m deep to escape the harsh conditions experienced in shallow soil of fluctuating extremes of temperature and moisture.

The ponding banks built from soil scraped below them had a lower capacity to pond water before spillage, but the undisturbed soil in their ponded areas grew better ground cover and the water from a small rain shower ponded over a larger area above the bank, thus irrigating more grass. Scraping soil from above the bank is warranted only where a sponge is required for calming the flow of water before it hits the bank. The challenge is to choose carefully where to spill the excess water from these 'buffer' check banks and do so calmly over as wide an extent as possible. The bunds should be only as wide as needed to 'take the hit', and the pacified flow should be intercepted and spread as close below as possible before the flow can accelerate (particularly on steeper slopes).

The bush filter lines are much cheaper than earthmoving, especially when labour is essentially free (students) or low cost (farm labourers) to the farmer, and they serve the dual purpose of filtering and reducing bush encroachment. However, they are likely to take much longer before effectively infiltrating rainwater to anywhere near the levels achieved by ditches and banks. Whether or not they are capable of self-reinforcement will depend on whether grass can establish fast enough to replace the filtering function of the decomposing branches, which largely depends on the grazing pressure being exerted by wild animals and livestock. Some maintenance and augmentation may be required, and this will depend on both grazing pressure and the quality of seasons.

It is too early to observe the microhabitat benefits expected from planted trees as they grow. Over the years, they are likely to improve soil conditions, not only through better nutrient cycling (Sandhage-Hofmann et al., 2015) but also through improved water cycling (Joffre & Rambal, 1988). The high death rate of tree seedlings initially planted below contour ditches could have been avoided by following the advice of Zimbabwean water harvester Zephaniah Phiri (Witoshynsky, 2000) to plant the water before planting the trees.

Since there is enormous variation in climatic conditions from year to year, monitoring should rely on contrast between treated and untreated sites rather than before and after measurements. Indicators related to soil moisture that can be measured easily are the depth to which rainwater percolated at the start of the rainy season in relation to water harvesting infrastructure (Zimmermann et al., 2015) and the extent of sprouting perennial plants in spring, at the end of the dry season.

Conclusion

No single technique for infiltrating more rainwater can be singled out as being better than others. Each has its own advantages and disadvantages that may better serve the particular circumstances experienced at any site and the objectives desired by the farmers. To recoup the high cost of earthmoving, the value of the resulting increase in production must be sufficiently large within an acceptable time frame. This requires a high survival rate and fast growth of valuable trees planted below contour ditches, and fast establishment of productive and nutritious grass above ponding banks. These challenges are being addressed by applying the lessons learned so far in this action research.

All of these innovative approaches should be viewed as tools in a diverse toolbox that allows intensified rangeland food production to be extended from traditional small family gardens to community gardens of tens of hectares or more. We have made a start and do not contend that we have a final product. It is probable that the combined efforts of families will extend and improve food production and production per human input and hectare. The potential rewards of localising the security and quality of key food needs have driven us to try many approaches in different environments, and we hope to develop a framework for wider adoption in different situations. The challenge now is to select tools and techniques in harmony with landscape patterns and processes to maximise the depth, breadth, and duration of positive soil moisture balance. We will then utilise that for a diversity of fruitful outcomes that suit local community needs.

It is also important that no single technique be viewed as a stand-alone entity. Since techniques that infiltrate more rainwater tend to treat only the symptoms of rangeland degradation, it will be necessary to integrate them with other techniques that address the root causes, such as through the appropriate management of grazing and fires.

The ditches, banks, and filters have started to regenerate water cycling, and the planted trees will eventually contribute to regenerating nutrient cycling. To replace the whole spectrum of minerals lost from the system over past decades, however, some inputs will be required (Zimmermann et al., 2017).

In cases where communities have access to the enhanced land, a concerted effort is needed to gain community ownership and leadership (governance) to ensure longevity and minimise theft and vandalism, preferably before projects commence.

Intensive management of relatively small areas fitting natural patterns and processes can not only reverse existing degradation processes but also improve productivity beyond good grazing condition. In the face of challenges such as climate change and increasing population pressure, localising diverse food security offers rural communities many benefits, including participation in the commercial economy.

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References

Australian Plants Society. (2010) *The long-stem planting guide*. http://www.tamariskcoalition.org/sites/default/files/resource-center-documents/Austrailian_Longstem_Guide.pdf

Andrews, P. (2008) *Beyond the brink – Peter Andrews' radical vision for a sustainable Australian landscape.* Harper Collins, Sydney.

Bais, H.P., Weir, T.L., Perry, L.G., Gilroy, S. & Vivanco, J.M. (2006) The role of root exudates in rhizosphere interactions with plants and other organisms. *Annual Review of Plant Biology*, **57**, 233–66.

Bastin, G.N., Tongway, D.J., Sparrow, A.D., Purvis, B. & Hindley, N.L. (2001) Soil and vegetation recovery following water ponding. *Range Management Newsletter*, **July 2001**, 1–7.

Craggs, G. (2017) *Rangelands: Critical to the environment and under constant threat.* Future Directions International, Dalkeith, Australia. http://www.futuredirections.org.au/publication/rangelands-critical-environment-constant-threat/

Critchley, W. (1991) *Looking after our land: soil and water conservation in dryland Africa*. Oxfam, Oxford, UK.

de Klerk, J.N. (2004) *Bush encroachment in Namibia*. Report on Phase 1 of the Bush Encroachment Research, Monitoring and Management Project, Ministry of Environment and Tourism, Windhoek.

Fynn, R. & Bonyongo, C. (2011) Functional conservation areas and the future of Africa's wildlife. *African Journal of Ecology*, **49**, 175–188.

Jo, H. & Park, H. (2017) Effects of pit plantings on tree growth in semi-arid environments. *Forest Science and Technology*, **13**, 66–70.

Joffre, R. & Rambal, S. (1988) Soil water improvement by trees in the rangelands of southern Spain. *Oecologia Plantarum*, **9**, 405–422.

Kaurivi, B. (2013) Why was bone meal in cattle feed banned in Namibia: link to mad-cow disease? *The Villager*, 16 September 2013.

Lancaster, B. (2013) *Rainwater harvesting for drylands and beyond. Volume 2. Water harvesting earthworks*. Rainsource Press, Tucson, AZ, USA.

Lau, B. & Reiner, P. (1993) 100 years of agricultural development in colonial Namibia: a historical overview of visions and experiments. *Archeia* **17**. National Archives of Namibia, Windhoek, Namibia.

Leakey, R.R.B. (2014) Twelve principles for better food and more food from mature perennial agroecosystems. *Perennial crops for food security - proceedings of the FAO expert workshop, 28–30 August 2013, Rome, Italy* (ed. by C. Batello, L. Wade, S. Cox, N. Pogna, A. Bozzini, and J. Choptiany), pp. 282–306. Food and Agriculture Organization (FAO), Rome.

Ludwig, J.A. & Tongway, D.J. (1995) Spatial organisation of landscapes and its function in semi-arid woodlands, Australia. *Landscape Ecology*, **10**, 51-63.

Mills, A.J., Milewski, A.V., Fey, M.V., Gröngröft, A., Petersen, A. & Sirami, C. (2013) Constraint on woody cover in relation to nutrient content of soils in western southern Africa. *Oikos*, **122**, 136–148.

Milton, S.J., Dean, R.J., du Plessis, M.A. & Siegfried, W.R. (1994) A conceptual model of arid rangeland degradation: the escalating cost of declining productivity. *BioScience*, **44**, 70–76.

Murirwa, K., Hagmann, J. & Chuma, E. (2001) Mainstreaming participatory approaches to soil and water conservation in Zimbabwe. *Farmer innovation in Africa: A source of inspiration for agricultural development* (ed. by C. Reij and A. Waters-Bayer), pp. 300–309. Earthscan, London, UK.

Pringle, H.J.R. & Tinley, K.L. (2003) Are we overlooking critical geomorphic determinants of landscape change in Australian rangelands? *Ecological Management and Restoration*, **4**, 180–186.

Pringle, H., Zimmermann, I. & Tinley, K. (2011) Accelerating landscape incision and the downward spiraling rain use efficiency of Namibian rangelands. *Agricola*, **21**, 43–52.

Sandhage-Hofmann, A., Kotzé, E., van Delden, L., Dominiak, M., Fouch, H.J., van der Westhuizen, H.C., Oomen, R.J., du Preez, C.C. & Amelung, W. (2015) Rangeland management effects on soil properties in the savanna biome, South Africa: a case study along grazing gradients in communal and commercial farms. *Journal of Arid Environments*, **120**, 14–25.

Shepard, M. (2013) *Restoration agriculture*. Acres USA, Austin, TX, USA.

Sianga, K., van Telgen, M., Vrooman, J., Fynn, R.W.S. & van Langevelde, F. (2017) Spatial refuges buffer rangelands against homogenisation and degradation by large herbivore populations and facilitate vegetation heterogeneity. *Koedoe*, **59,** a1434. https://doi.org/10.4102/koedoe.v59i2.1434

Stanton, C. & Waterson, D. (2007) *Introduction to soil erosion. Edition 1.* Vegetation and Land Management, Northern Territory Government, Alice Springs.

Thurston, H.D. (1997) *Slash/mulch systems.* Sustainable methods for tropical agriculture. Intermediate Technology Publications, London.

Tiffen, M., Mortimore, M. & Gichuki, F. (1994) *More people, less erosion: Environmental recovery in Kenya*. John Wiley & Sons, Chichester, UK.

Tinley, K.L. & Pringle, H.J.R. (2013a) *Rangeland rehydration: field guide*. Rangelands NRM, Western Australia.

Tinley, K.L. & Pringle, H.J.R. (2013b) *Rangeland rehydration: the manual*. Rangelands NRM, Western Australia.

Ward, D. & Ngairorue, B.T. (2000) Are Namibia's grasslands desertifying? *Journal of Range Management*, **53**, 138–144.

Whitlock, R. (2015) Research on Bakoni ruins of South Africa debunks colonial perceptions of primitivism. *Ancient Origins.* http://www.ancient-origins.net/news-history-archaeology/research-bakoni-ruins-south-africa-debunks-colonial-perceptions-020418

Witoshynsky, M. (2000) *The water harvester: episodes from the inspired life of Zephaniah Phiri*. Weaver Press, Harare, Zimbabwe.

Zimmermann, I., Nghikembua, M., Shipingana, D., Aron, T., Groves, D. & Marker, L. (2017). The influence of two levels of debushing in Namibia's thornbush savanna on overall soil fertility, measured through bioassays. *Namibian Journal of Environment*, **1A**, 52–59.

Zimmermann, I., Pringle, H.J.R., Shamathe, K. & Kahl, U. (2015) First steps of converting bush-encroached Namibian rangeland into a fruitful landscape. *Collection of extended abstracts for the international symposium: Silviculture and Management of Dryland Forests*, pp. 29–31. Department of Forest and Wood Science, Stellenbosch University, in collaboration with IUFRO Unit 1.02.05. Stellenbosch, South Africa, 16–19 March 2015.

References [CrossRef]

Australian Plants Society. (2010) *The long-stem planting guide*. http://www.tamariskcoalition.org/sites/default/files/resource-center-documents/Austrailian_Longstem_Guide.pdf

Andrews, P. (2008) *Beyond the brink – Peter Andrews' radical vision for a sustainable Australian landscape.* Harper Collins, Sydney.

Bais, H.P., Weir, T.L., Perry, L.G., Gilroy, S. & Vivanco, J.M. (2006) The role of root exudates in rhizosphere interactions with plants and other organisms. *Annual Review of Plant Biology*, **57**, 233–66. CrossRef

Bastin, G.N., Tongway, D.J., Sparrow, A.D., Purvis, B. & Hindley, N.L. (2001) Soil and vegetation recovery following water ponding. *Range Management Newsletter*, **July 2001**, 1–7.

Craggs, G. (2017) *Rangelands: Critical to the environment and under constant threat*. Future Directions International, Dalkeith, Australia. http://www.futuredirections.org.au/publication/rangelands-critical-environment-constant-threat/

Critchley, W. (1991) *Looking after our land: soil and water conservation in dryland Africa*. Oxfam, Oxford, UK. CrossRef

de Klerk, J.N. (2004) *Bush encroachment in Namibia*. Report on Phase 1 of the Bush Encroachment Research, Monitoring and Management Project, Ministry of Environment and Tourism, Windhoek.

Fynn, R. & Bonyongo, C. (2011) Functional conservation areas and the future of Africa's wildlife. *African Journal of Ecology*, **49**, 175–188. CrossRef

Jo, H. & Park, H. (2017) Effects of pit plantings on tree growth in semi-arid environments. *Forest Science and Technology*, **13**, 66–70. CrossRef

Joffre, R. & Rambal, S. (1988) Soil water improvement by trees in the rangelands of southern Spain. *Oecologia Plantarum*, **9**, 405–422.

Kaurivi, B. (2013) Why was bone meal in cattle feed banned in Namibia: link to mad-cow disease? *The Villager*, 16 September 2013.

Lancaster, B. (2013) *Rainwater harvesting for drylands and beyond. Volume 2. Water harvesting earthworks*. Rainsource Press, Tucson, AZ, USA.

Lau, B. & Reiner, P. (1993) 100 years of agricultural development in colonial Namibia: a historical overview of visions and experiments. *Archeia* **17**. National Archives of Namibia, Windhoek, Namibia.

Leakey, R.R.B. (2014) Twelve principles for better food and more food from mature perennial agroecosystems. *Perennial crops for food security - proceedings of the FAO expert workshop, 28–30 August 2013, Rome, Italy* (ed. by C. Batello, L. Wade, S. Cox, N. Pogna, A. Bozzini, and J. Choptiany), pp. 282–306. Food and Agriculture Organization (FAO), Rome.

Ludwig, J.A. & Tongway, D.J. (1995) Spatial organisation of landscapes and its function in semi-arid woodlands, Australia. *Landscape Ecology*, **10**, 51-63. CrossRef

Mills, A.J., Milewski, A.V., Fey, M.V., Gröngröft, A., Petersen, A. & Sirami, C. (2013) Constraint on woody cover in relation to nutrient content of soils in western southern Africa. *Oikos*, **122**, 136–148. CrossRef

Milton, S.J., Dean, R.J., du Plessis, M.A. & Siegfried, W.R. (1994) A conceptual model of arid rangeland degradation: the escalating cost of declining productivity. *BioScience*, **44**, 70–76. CrossRef

Murirwa, K., Hagmann, J. & Chuma, E. (2001) Mainstreaming participatory approaches to soil and water conservation in Zimbabwe. *Farmer innovation in Africa: A source of inspiration for agricultural development* (ed. by C. Reij and A. Waters-Bayer), pp. 300–309. Earthscan, London, UK.

Pringle, H.J.R. & Tinley, K.L. (2003) Are we overlooking critical geomorphic determinants of landscape change in Australian rangelands? *Ecological Management and Restoration*, **4**, 180–186. CrossRef

Pringle, H., Zimmermann, I. & Tinley, K. (2011) Accelerating landscape incision and the downward spiraling rain use efficiency of Namibian rangelands. *Agricola*, **21**, 43–52.

Sandhage-Hofmann, A., Kotzé, E., van Delden, L., Dominiak, M., Fouch, H.J., van der Westhuizen, H.C., Oomen, R.J., du Preez, C.C. & Amelung, W. (2015) Rangeland management effects on soil properties in the savanna biome, South Africa: a case study along grazing gradients in communal and commercial farms. *Journal of Arid Environments*, **120**, 14–25. CrossRef

Shepard, M. (2013) *Restoration agriculture*. Acres USA, Austin, TX, USA.

Sianga, K., van Telgen, M., Vrooman, J., Fynn, R.W.S. & van Langevelde, F. (2017) Spatial refuges buffer rangelands against homogenisation and degradation by large herbivore populations and facilitate vegetation heterogeneity. *Koedoe*, **59,** a1434. CrossRef

Stanton, C. & Waterson, D. (2007) *Introduction to soil erosion. Edition 1.* Vegetation and Land Management, Northern Territory Government, Alice Springs.

Thurston, H.D. (1997) *Slash/mulch systems.* Sustainable methods for tropical agriculture. Intermediate Technology Publications, London.

Tiffen, M., Mortimore, M. & Gichuki, F. (1994) *More people, less erosion: Environmental recovery in Kenya*. John Wiley & Sons, Chichester, UK.

Tinley, K.L. & Pringle, H.J.R. (2013a) *Rangeland rehydration: field guide*. Rangelands NRM, Western Australia.

Tinley, K.L. & Pringle, H.J.R. (2013b) *Rangeland rehydration: the manual*. Rangelands NRM, Western Australia.

Ward, D. & Ngairorue, B.T. (2000) Are Namibia's grasslands desertifying? *Journal of Range Management*, **53**, 138–144. CrossRef

Whitlock, R. (2015) Research on Bakoni ruins of South Africa debunks colonial perceptions of primitivism. *Ancient Origins.* http://www.ancient-origins.net/news-history-archaeology/research-bakoni-ruins-south-africa-debunks-colonial-perceptions-020418

Witoshynsky, M. (2000) *The water harvester: episodes from the inspired life of Zephaniah Phiri*. Weaver Press, Harare, Zimbabwe.

Zimmermann, I., Nghikembua, M., Shipingana, D., Aron, T., Groves, D. & Marker, L. (2017). The influence of two levels of debushing in Namibia's thornbush savanna on overall soil fertility, measured through bioassays. *Namibian Journal of Environment*, **1A**, 52–59.

Zimmermann, I., Pringle, H.J.R., Shamathe, K. & Kahl, U. (2015) First steps of converting bush-encroached Namibian rangeland into a fruitful landscape. *Collection of extended abstracts for the international symposium: Silviculture and Management of Dryland Forests*, pp. 29–31. Department of Forest and Wood Science, Stellenbosch University, in collaboration with IUFRO Unit 1.02.05. Stellenbosch, South Africa, 16–19 March 2015.

Food security

Food security through improved farm management

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Abstract: The Southern African Development (SADC) region is already experiencing the adverse effects of climate change leading to low food productivity and decreasing food security at the household level. The cropping seasons tend to start later and last for a shorter period of time. Unfortunately, this problematic reality is complexed by low awareness in the community regarding climatic changes and several other biotic and abiotic factors. The agriculture tasks in SASSCAL investigated alternative farm management approaches for sustainable agricultural production in farming communities of central, southern and western Zambia (Tasks 157 and 188), in Botswana at several locations throughout the country (Tasks 316, 314 and 308), eastern and central Angola (Task 144), and in the Kavango Regions of Namibia (Tasks 051 and 044). This overview chapter will describe the different farming systems encountered during the studies of SASCCAL and outline potential impacts of climate change on subsistence, commercial and investor-driven agriculture. The reasons for low agricultural crop performance and possible remedies in the SASSCAL region will be discussed in this chapter.

Resumo: A região de Desenvolvimento da África Austral (SADC) está já a sentir os efeitos adversos das alterações climáticas, levando à baixa produtividade alimentar e à diminuição da segurança alimentar ao nível doméstico. As épocas de colheita têm tendência a começar mais tarde e duram menos tempo. Infelizmente, esta realidade problemática é complicada pela reduzida sensibilização comunitária em relação às alterações climáticas e a diversos outros factores bióticos e abióticos. As equipas do SASSCAL focadas na agricultura investigaram abordagens alternativas de gestão agrícola para a produção sustentável nas comunidades agrícolas do centro, Sul e Oeste da Zâmbia (Equipas 157 e 188), do Botswana em diversos locais do país (Equipas 316, 314 e 308), do Este e centro de Angola (Equipa 144) e das Regiões do Kavango na Namíbia (Equipas 051 e 044). Este capítulo irá descrever resumidamente os diferentes sistemas agrícolas observados durante os estudos realizados pelo SASSCAL e delinear os potenciais impactos das alterações climáticas na agricultura de subsistência, comercial e orientada para investidores. As razões para o baixo desempenho das culturas e as possíveis soluções na região do SASSCAL serão discutidas neste capítulo.

Introduction

According to the outcomes of the World Food Summit (1996), food security exists when all people, always, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life. It is a major challenge to achieve food security globally for a growing world population. Many factors affect food availability for people in different parts of the world. A mixture of ecological, sociological, political and economic factors has a direct influence on the production, quality, consumption, and distribution of food. Additional challenges to attaining food security arise due to global change and the depletion of soils as a consequence of unsustainable agricultural practices. Thus, there is urgency to develop alternative, sustainable farming practices that are able to produce an optimal yield on limited space and at the same time conserve nature to allow continued benefits of ecosystem services.

In the Southern African Development Community (SADC) region, food security issues have often taken centre stage, but there is still a lack of lasting solutions to securing the nutrition of all. At the producer level, one reason for the lack of progress is that agricultural production does not necessarily follow advice based on empirical research data. Moreover, empirical evidence for sustainable production in small-scale agriculture is still scarce (Steward et al., 2014). Most farmers have no access to recommendations based on scientific studies and thus continue to use conventional approaches established many years ago, that are designed for large-scale industrialised agriculture and are not appropriate for small-scale systems (Holt-Giménez & Altieri 2013). A recent review by Garibaldi et al., (2017) shows that empirical evidence on alternative farming approaches is mostly generated for industrialised agriculture but very scarce for farms operating on a small scale. The contributing authors in this section of the book emphasise that research has to focus on management alternatives for sustainable land use and their implications for people, by taking socio-economic parameters into account. Interdisciplinary research, and the dissemination of its findings to stakeholders, has to be improved in order to promote better land management and higher yields (Francis et al. 2003).

The SASSCAL agriculture tasks investigated alternative management approaches for sustainable agricultural production, defining food production and availability in farming communities of central, southern, and western Zambia (tasks 157 and 188), Botswana (region east to west and south to north on a rainfall gradient; tasks 316, 314 and 308), eastern and central Angola (task 144), and Namibia (in the Kavango region, mostly along the Kavango River; tasks 051 and 044).

This chapter will give a brief overview of the different farming systems encountered during the studies in the SASSCAL region and the potential impacts of investor-driven agriculture, and propose reasons for poor agricultural crop performance. Problems and solutions for the agricultural sector in the SASSCAL region will be discussed. This introduction will serve as a prelude to the chapters compiled for the Agriculture thematic area of the SASSCAL programme.

Farming systems within southern Africa

Different agro-ecological zones of southern Africa

For more than 30 years, the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) have developed the methodology of Agro-Ecological Zones (AEZ) with the aim to assess the potential and resources of a given region and its suitability for agricultural production (FAO, 2017). According to the FAO, southern Africa encompasses at least eight agro-ecological zones from tropical to arid landscapes (depending on the underlying classification). There are different approaches to dividing these zones in terms of climate, soil type, landcover, etc., so the number of zones varies accordingly. However, there is a similarity of farming systems to be found across all countries in the SADC region. Smallholder farms and large-scale commercial farms coexist, in both cases comprising a mixture of crop farming, animal husbandry, and horticulture, depending on the prevailing climatic factors (FAO/World Bank, 2001). In most studies up to now, agro-ecological zones have been assumed as a stable factor, yet these zones are by definition a function of climate and it is likely that they might shift according to climatic changes (World Bank 2008). This will require adaptive decisions by farmers and consequently will result in a change of farming practices and systems. In general, it is assumed that in the case of decreasing or more variable precipitation, farmers relying on rainfed agriculture will emigrate or switch to livestock production. Livestock producers respond by switching from cattle to sheep and goats if the climate becomes drier (World Bank 2008).

Subsistence agriculture

For most of the SADC region, smallholder farmers form the majority of the farming populations and their subsistence is hand-to-mouth; very rarely do they have excess produce to sale, especially with the advent of climate change (SADC, 2017). In many areas of southern Africa, smallholder farmers are confronted with low soil fertility, highly variable rainfall with risk of drought or flood, soil erosion, and other constraints. Malnutrition and a high degree of food insecurity are the result (Thierfelder et al., 2013). The one common feature of crop production in the SADC region is fluctuating and steadily declining crop yields, as shown in Figure 1 for the case of maize production in Zimbabwe (Thierfelder et al., 2013). To overcome the low soil fertility, shifting cultivation is practised. This involves the clearing of woodlands for new fields with subsequent burning of the biomass. The ash provides a pulse in nutrients supporting cultivation over a number of years before a fallow period is required (Ruthenberg et al., 1980). However, the burning also causes substantial loss of nutrients, especially nitrogen and phosphate, through volatilisation (Giardina 2000). Due to population increase leading to a higher demand for new areas for agriculture and the change in land ownership policies in the recent past, shifting cultivation is becoming unsustainable (Von Braun et al., 2003): it is no longer easy to find, shift and cultivate new areas of fertile soil. As a consequence, smallholder agricultural systems formerly using shifting cultivation are gradually being transformed into semi-permanent systems, as documented for the Okavango Basin (Gröngröft et al., 2015).

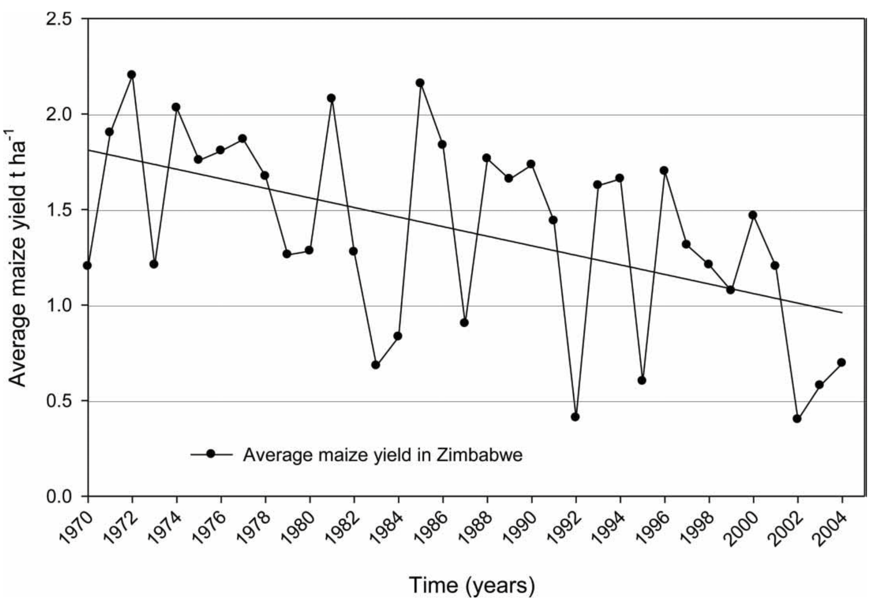

Figure 1: Average maize yield in Zimbabwe (in t ha–1), 1970–2004 (CSO, 1987; CSO, 1984–1989; Adopted from FAOSTAT, 2004).

Food security

In spite of these challenges, smallholders rather than large-scale farming enterprises are still the backbone of food security in the SASSCAL region (Tscharntke et al., 2012). However, the interactions of climate change and poor farming methods are starting to pose a threat to food security (Chilonda et al., 2006; Chilonda & Minde 2007; SADC, 2017). This is illustrated by the fact that governments within SADC have had to supply food aid in order to avert calamities due to famine. Namibia had to introduce a food bank system to secure food provisions to its people during times of adversity. Other SADC countries have different schemes of food aid (The Namibian, 2016). Since most farmers rely on subsistence agriculture, this system is the main focus of the agricultural research in SASSCAL.

Commercial, investor-driven agriculture

It should not be overlooked that within the SADC region there is also commercial large-scale farming. The sector covers crops, animals and horticultural production (SADC, 2017), but there are concerns about its impacts. Industrialised agriculture often exploits natural resources that, at a household level, are important for poverty alleviation. Although productivity is generally higher on commercial farms, this agricultural sector is based on generating individual profit gains. Benefits accrue to the few landowners, whilst the vast majority of the people, who are often employed as labourers and casual workers, become victims to the phenomenon of land-grabbing. This begs the important question: are commercial, large-scale farms an acceptable solution to food insecurity in the SADC? Or should we instead empower small-scale farmers to achieve better productivity? Might there be an underlying and confounding factor of reorganising land tenure and resettlement?

Reasons for low crop performance in the SADC region

Poor performance in agriculture can be defined as agricultural practice or management strategy that fails to meet its intended objective. The economic objective in agricultural practices is usually emphasised: to ensure food security and improvement of livelihoods for rural households. If this objective is not met, then the agricultural performance is deemed to be poor. It is worth noting that this definition is based on measuring the output only and does not include the *process* of obtaining the output, including the important consideration of the energy return of inputs.

There are many reasons which lead to poor or low agricultural performance. For example, one could point to the negative impact on resource-poor farmers of the monocultural seed practices promoted by large seed companies like Bayer and Monsanto. Other commonly cited reasons for poor agricultural performance are unfavourable biotic and environmental factors. The environmental factors include nutrient-poor soils or poor water availability impacting on crop growth, excessive temperatures, and sometimes floods. These factors can be considered as ecological disadvantages, since their occurrence is linked to the geography of the land available for cultivation and its attributes. The unfavourable biotic factors include prevalence of pests and microbial pathogens on crops. In addition, there are also badly adapted or poor farming methods and farm management practices that lead to poor crop yields, whilst socio-ecological or demographic perspectives can also come into play. Countries that have experienced events leading to internal displacement of people have been known to be characterised by poor agricultural performance (FAO, 2006, Akinsanmi & Abrahams, 2013).

Problems and challenges for agriculture in the SASSCAL region

Conflicting land uses, human–wildlife conflicts

Some of the biggest challenges agriculture is facing in the SASSCAL region include conflicts between humans and wildlife, between landholder policies, and between land-use priorities. In some places, land that has been set aside as conservation areas and nature reserves to protect the native flora and fauna is being used by humans for settlement and agriculture. This often results in human–wildlife conflicts, since wild animals encounter the human settlements, attack people, or devastate their crop fields, whilst poor people poach on the wildlife for bushmeat or ivory, killing protected and endangered species (see the article by Nyirenda et al., 2018). Similarly, land that has previously been set aside for commercial agriculture is sometimes reallocated for urban settlements, leading to shortage of land for farming purposes. This becomes a trigger for land grabbing and vicious cycles of conflict between the smallholder and commercial farmers, and brings rise to the perennial issue of overhauling the land tenure system (The Namibian, 2017). Such policy shifts are frequent and lead to poor agricultural performance and food insecurity in the long run. Sustainable land planning and management is needed to mitigate these conflicts, involving close collaboration between the governing structures dealing with nature conservation and environmental protection, agricultural production, and planning of settlements and infrastructure.

Global change: change of lifestyle to modern consumerism

A notable, and perhaps alarming, global trend is the change of an agrarian to modern consumerist lifestyle (Bruinsma, 2003). This has the eventual effect of reducing food security from household to national levels in developing countries, which are dominated by agrarian households. The consumerist lifestyle trend is leading to agriculture being given low priority, both as a means of production and source of livelihoods. The consequence is reduced production on small farms. This shift can generally be managed adaptively, such that farming practices are mechanised and improved. However, technological improvement and support need to be available to small rural communities, including a better infrastructure and therefore access to markets, and improved storage facilities and value chain models for agricultural products (Chilonda, 2006). Such enabling conditions allow farmers to improve their income and act as producers and consumers at the same time. A less easy root cause of low productivity to address is that of climate change.

What solutions can research offer?

Reaching comprehensive solutions to Africa's low agricultural productivity is a mammoth task. The problems and challenges to agricultural productivity, highlighted above, manifest themselves at varying scales and degrees of severity within the SADC region. This means there cannot be a "one-size-fits-all" toolkit to solve the intricately compounded causes. Some of the solutions will be generated via dedicated research efforts for each scenario. Management systems such as "conservation agriculture" have been tabled as possible solutions to the problem of landscapes increasingly degraded by erosion and excessive and injudicious use of chemical fertilisers and pesticides. To arrive at recommendations for small-scale farmers that are practicable and feasible, alternative management practices have to be developed and tested at a local to regional level. The introduction alone of, for example, a new seed variety or type of fertiliser, will not be enough. Instead, various simultaneous changes are usually needed; whilst more complex to implement, they offer higher and more stable yields when successful (Thierfelder et al., 2013).

There is a need to conduct empirical research to improve varieties of crops and animals that are optimally adapted to local conditions for enhanced productivity (Von Braun, 2003) and allow farmers to adapt to changing conditions. This requires increased effort in seamless germplasm evaluation of local varieties used in crop production and horticulture in the SADC region. Clear evidence of current climate change underlines the necessity to change sowing dates of crops and use adapted cultivars.

As in many parts of the SASSCAL region, yields are nitrogen limited (Gröngröft et al., 2015). Enhancing N supply to the soil by using environment friendly nitrogen fixing plants (legumes) and microorganisms is another sustainable solution, especially when accompanied by conservation management approaches applied to soils and ecosystem services including nutrient supply, natural pest control and pollination.

Political factors affect food security and include war, political stability, emigration/immigration, land tenure, and government policies. For this reason, evaluation of local food production (yield, productivity) alone provides a very incomplete picture of the food security situation (UN/AU, 2003, Akinsanmi and Abrahams, 2013). What is needed is interdisciplinary research into food security.

The agricultural research topics within SASSCAL shared similar characteristics in terms of demographics, gender, and cropping systems, even though the climate ranges from arid and semi-arid to moist and wet conditions. Scientific research was carried out on improved farm management practices for cropping systems, such as minimum tillage, residue retention/soil cover, crop rotation with legumes, intercropping with legumes, and improved fertiliser use efficiency. Other practices investigated included appropriate planting dates and selection of improved varieties to adapt to changing climatic conditions.

SASSCAL Supported Agriculture Tasks: A Results Summary

The effect of improved practices on soil fertility, water stress, pests and diseases, weeds, and yield was measured and compared to conventional farm practices such as disc harrowing, planting densities, weeding and chemical fertiliser application. Conservation farm management practices were found to improve soil fertility by reducing soil acidity and improving the nutrient status of the soil through inputs of organic matter. In some soils, the acidity was reduced from pH 4 to pH 5.6 by the third season of adopting practices that increased soil organic matter from less than 1% to above 2% (Tasks 157 and 144). This resulted in overall improvement in yields and productivity, demonstrating how conservation agriculture has the potential to improve the food security situation in these farming communities. Notably, the best outcome was achieved when all principles of conservation agriculture (minimum tillage, residue retention/soil cover, crop rotation with legumes, intercropping with legumes, and improved fertiliser use efficiency, planting dates and selection of improved varieties) were adhered to.

Another positive effect was the very good performance of locally adapted germplasm, so that the participating local farmers were able to produce their own maize and cowpea seeds. This will ensure the timely availability of good quality, adapted germplasm that gives high yield under stress conditions. Seed production is of high value and can contribute to income security of the household and allow for investment in other farm enterprises. Availability of good quality seed has traditionally been a challenge as it is controlled by global corporations distributing patented hybrid varieties at costs that limit production. Local seed production will make the farmers more independent from global enterprises. This gave a good opportunity for technology transfer to farmers on seed production (Batlang et al., 2018).

However, a few challenges remain, especially natural stresses on crop production such as water stress (either too dry or too wet), varying and unpredictable length of growing season, and pest and disease pressures. These factors may cause lower yields than expected from the agronomic potential of improved crop varieties (SADC 2012). In some areas in and around land used for game management, human–wildlife conflicts were also cited as posing a threat to increased productivity, especially during the high stress months of the dry season (Tasks 314 and 190). In game management areas, wildlife is under protection and controlled utilisation. A lasting solution to human–wildlife conflict is still seemingly elusive, for when people take space for wildlife, the wild animals respond by grazing on planted crops nearby (Nyirenda et al., 2018).

To mitigate these stresses, practices that improve resilience of crop plants to water stress and the pressure of pests and disease were investigated. Studies on germplasm selection for water stress studies were conducted and confirmed the availability of legume and cereal germplasm with traits for water stress resilience within the SASSCAL region (Tasks 157, 044, 308, and 316). Changing climate patterns have been reported in the SASSCAL region, resulting in a general shift in planting season (dates) and length of growing season. Investigations on appropriate planting dates for legumes and cereals in different regions confirmed this shift and planting dates were selected using available 5–10 year weather data (Tasks 308, 144, and 051). To mitigate pest and disease stress, biological control practices, such as inter-cropping with legumes, were investigated. The diversity and abundance of insect pests and natural enemies was observed and found to be more prevalent in cereal-legume intercrops than in monocultures of cereal or legume (Tasks 044, 316, and 051). The increase in pests had a negative impact on yields, though further research is needed in this regard.

Conclusion and Perspectives

The current sub-optimal performance of cropping systems in the SASSCAL region directly and negatively affects the food security situation, especially of the rural population. Low yields of cereals (maize 1.15 tonnes/ha, rice 0.5 tonnes/ha) and legumes (common beans 1.15 tonnes/ha, soya beans 1.54 tonnes/ha) have been reported in the region, especially among the majority (70%) smallholder farmers during the period 2013–16 (SADC, 2017). Improved farm management practices can improve yields, increase the performance (productivity) of cropping systems, and achieve food security in the SASSCAL region. Addressing soil fertility issues through conservation tillage, inputs of organic matter, adapted crop rotation, and improved fertiliser use, was found to improve yields for maize and beans (Tasks 147 and 157). Crop rotation with legumes was found to help satisfy the nitrogen requirement of beans and successor maize crops (Task 316). Clearly, adopting better farm management practices in cropping systems of the SASSCAL region is a promising option for improving the food security situation in the context of changing weather and climate. It is of concern that these "promising options" remain at the experimental level; their widespread adoption in the SASSCAL region, as in many parts of the developing world where food security is low, is all too uncommon. An agricultural extension service informed of the research results and trained to promote new agricultural practices is urgently needed in all SASSCAL countries.

However, high yields and increased productivity alone may not adequately improve food security, since other location-specific factors come into play. While high yields will provide sufficient, quality food at required times to meet dietary needs, physical and economic access to food may still be limited to both rural and urban household settings (Akinsanmi & Abrahams, 2013). Value chain investigations revealed that there was a positive impact of value addition on household livelihoods and the food security situation. There is a need to further investigate factors that limit physical and economic access to food in the SASSCAL region in order to provide solutions for further improvement in food security. It is also important to make a detailed study of the historical development of the farming systems of the SADC region and then examine where things may have gone wrong and seek reversal or remedy.

The research articles in this book (by various contributing authors of the SASSCAL Agriculture Tasks) provide scientific evidence that farm management practices can improve the performance of cropping systems. Farmers are therefore encouraged to adopt these practices to ensure that their food and income security requirements are met. The food security situation can be improved by increasing food production and by addressing factors that limit physical and economic access to food.

It is anticipated that, after reading this section on agriculture, an open-minded approach to increasing food security will be followed, embracing some of the non-conventional ideas discussed in these chapters (e.g. using rhizobial bacteria to improve plant growth and development). The research ideas presented in these chapters are a direct outcome of farmer–researcher participatory interactions and should therefore be easy to implement in full on a larger scale. It is important to prioritise participatory approaches – at least until better empowerment tools come in – when dealing with complex matters like climate change effects. Climate change impacts to the SADC region are already signaling that now is the time to develop local crops and farming methods that, after millennia of evolution, are resilient and adapted to local environments. Perhaps this way we may improve the livelihoods of the rural population and combat climate change effects, which have a negative bearing on food security in the SASSCAL region. One can only remain hopeful that after reading these chapters, farmers and their practices will change. Furthermore, it is also hoped that the erroneous reasons given on why there is current underperformance of cropping systems will be abandoned by all stakeholders in the SASSCAL region and that of the wider SADC.

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References

African Union New Partnership for Africa's Development (UN/NEPAD 2003). Comprehensive Africa Agriculture Development Program (CAADP). Midrand, South Africa

Akinsanmi T. and Abrahmans L. (2013) Developing a framework for a community informatics policy networks: Agriculture for rural development in Southern Africa Report.

Batlang, U., King Jr., C., Ngwako, S., Nkomazana, C., Malambane, G., Mpuisang, T., Moroke, T.S., Mashungwa, G.N., Bagwasi, G., Pule-Meulenberg, F., Ng'uni, D. & Munkombwe, G. (2018) Germplasm evaluation for climate adaptation and drought tolerance: The cases of local varieties of maize in Zambia and cowpea in Botswana. This volume.

Bruinsma, J. (ed) 2003 World agriculture: towards 2015/2030: an FAO perspective. FAO/Earthscan: Rome and London.

Chilonda, P. & Minde I.J. (2007), Regional strategic analysis and knowledge support for Southern Africa, (RESAKSS-SA), Discussion Paper No. 1, 2007 ReSAKSS-SA: Pretoria.

Chilonda, P., Machethe, C. & Minde I.J. (2006) Poverty, food security and agricultural trends in Southern Africa, ReSAKSS-SA. Discussion Paper No. 3, 2006 ReSAKSS-SA: Pretoria.

FAO (2006) FAOSTAT data. Food and Agriculture Organization of the United Nations, Rome. Available online at http://faostat.external.fao.org/default.jsp

FAO/World Bank (2001) Farming Systems and Poverty: Improving farmers' livelihoods in a changing world, FAO and World Bank: Rome and Washington D.C.

Food and Agricultural Organization (FAO 2008)

Francis, C., Lieblein, G., Gliessman, S., Breland, T.A., Creamer, N., Harwood, R., Salomonsson, L., Helenius, J., Rickerl, D., Salvador, R., Wiedenhoeft, M., Simmons, S., Allen, P., Altieri, M., Flora, C. & Poincelot, R. (2003) Agroecology: The Ecology of Food Systems. *Journal of Sustainable Agriculture*, **22**, 99–118.

Garibaldi, L.A., Gemmill-Herren, B., D'Annolfo, R., Graeub, B.E., Cunningham, S.A. & Breeze, T.D. (2017) Farming Approaches for Greater Biodiversity, Livelihoods, and Food Security. *Trends in Ecology and Evolution*, **32**, 68–80.

Giardina, C., Sanford, R., Døckersmith, I. & Jaramillo, V. (2000). The effects of slash burning on ecosystem nutrients during the land preparation phase of shifting cultivation. *Plant and Soil* 220:247–260

Gröngröft, A., Azebaze, N., Brown, L., Cauwer, V. De, Domptail, S., Erb, C., Falk, T., Finckh, M., Göhmann, H., Gwatidzo, C., Hinz, M., Huber, K., Jürgens, N., Korn, E., Kowalski, B., Kralisch, S., Landschreiber, L., Lubinda, A., Luther-Mosebach, J., Maiato, F., Murray-Hudson, M., Pröpper, M., Reinhold, B., Revermann, R., Simfukwe, M., Stellmes, M., Stirn, S., Thito, K., Tsheboeng, G., Weber, T., Wehberg, J., Weinzierl, T., Zimmermann, I., 2015. Key findings and recommendations, in: Pröpper, M., Gröngröft, A., Finckh, M., Stirn, S., De Cauwer, V., Lages, F., Masamba, W., Murray-Hudson, M., Schmidt, L., Strohbach, B., Jürgens, N. (Eds.), The Future Okavango – Findings, Scenarios and Recommendations for Action. Research Project Final Synthesis Report 2010 — 2015. University of Hamburg, Hamburg, pp. 53–96.

Holt-Giménez, E. & Altieri, M.A. (2013) Agroecology, Food Sovereignty, and the New Green Revolution. *Agroecology and Sustainable Food Systems*, **37**, 90–102.

Nyirenda, V.R., Kaoma, C. & Nyirongo, S. (2018) Farmer-wildlife conflicts in rural areas of eastern Zambia. This volume.

Ruthenberg, H., MacArthur, J. D., Zandstra, H. D. & Collinson, M.P. (1980) Farming systems in the tropics. Clarendon Press, New York

SADC Food Security Quarterly Update, March 2017

SADC Policy Paper on Climate Change: Assessing the Policy Options for SADC Member States (2012)

Steward, P.R., Shackelford, G., Carvalheiro, L.G., Benton, T.G., Garibaldi, L.A. & Sait, S.M. (2014) Pollination and biological control research: are we neglecting two billion smallholders. *Agriculture & Food Security*, **3**, 5.

The Namibian Newspaper, 22 June 2016: Namibia to roll out food bank programme.

The Namibia Newspaper, 21 July 2017: Towards the Peoples Land Conference.

Thierfelder, C., Rusinamhodzi, L., Ngwira, A.R., Mupangwa, W., Nyagumbo, I., Kassie, G.T. & Cairns, J.E. (2013) Conservation agriculture in Southern Africa: Advances in Knowledge. Renewable Agriculture and Food Systems pp.1–21.

Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J. & Whitbread, A. (2012) Global food security, biodiversity conservation and the future of agricultural intensification. Biol. Conserv. 151, 53–59. doi:10.1016/j.biocon.2012.01.068

Von Braun, J., Hazell, P., Hoddinott, J. & Babu S. (2003) Achieving long term food security in southern Africa: International perspectives, investment strategies and lessons. Key note paper prepared for the southern Africa regional conference on 'Agricultural recovery, trade and long-term food security', March 26–27: Gaborone, Botswana.

References [CrossRef]

African Union New Partnership for Africa's Development (UN/NEPAD), 2003. Comprehensive Africa Agriculture Development Program (CAADP). Midrand, South Africa

Akinsanmi T and Abrahmans L, 2013, Developing a framework for a community informatics policy networks: Agriculture for rural development in Southern Africa Report.

Batlang, U., King Jr., C., Ngwako, S., Nkomazana, C., Malambane, G., Mpuisang, T., Moroke, T.S., Mashungwa, G.N., Bagwasi, G., Pule-Meulenberg, F., Ng'uni, D. & Munkombwe, G. (2018) Germplasm evaluation for climate adaptation and drought tolerance: The cases of local varieties of maize in Zambia and cowpea in Botswana. This volume. CrossRef

Bruinsma, J. (ed). 2003. World agriculture: towards 2015/2030: an FAO perspective. FAO/ Earthscan: Rome and London.

Chilonda P and Minde IJ, 2007, Regional strategic analysis and knowledge support for Southern Africa, (RESAKSS-SA), Discussion Paper No. 1, 2007 ReSAKSS-SA: Pretoria.

Chilonda P., Machethe C. and Minde I.J. 2006. Poverty, food security and agricultural trends in Southern Africa, ReSAKSS-SA. Discussion Paper No. 3, 2006 ReSAKSS-SA: Pretoria.

FAO 2006. FAOSTAT data. Food and Agriculture Organization of the United Nations, Rome. Available online at http://faostat.external.fao.org/default.jsp

FAO/World Bank, 2001, Farming Systems and Poverty: Improving farmers' livelihoods in a changing world, FAO and World Bank: Rome and Washington D.C.

Food and Agricultural Organization (FAO), 2008

Francis, C., Lieblein, G., Gliessman, S., Breland, T.A., Creamer, N., Harwood, R., Salomonsson, L., Helenius, J., Rickerl, D., Salvador, R., Wiedenhoeft, M., Simmons, S., Allen, P., Altieri, M., Flora, C. & Poincelot, R. (2003) Agroecology: The Ecology of Food Systems. *Journal of Sustainable Agriculture*, **22**, 99–118. CrossRef

Garibaldi, L.A., Gemmill-Herren, B., D'Annolfo, R., Graeub, B.E., Cunningham, S.A. & Breeze, T.D. (2017) Farming Approaches for Greater Biodiversity, Livelihoods, and Food Security. *Trends in Ecology and Evolution*, **32**, 68–80. CrossRef

Giardina, C., Sanford, R., Døckersmith, I. and Jaramillo, V. 2000. The effects of slash burning on ecosystem nutrients during the land preparation phase of shifting cultivation. *Plant and Soil* 220:247–260. CrossRef

Gröngröft, A., Azebaze, N., Brown, L., Cauwer, V. De, Domptail, S., Erb, C., Falk, T., Finckh, M., Göhmann, H., Gwatidzo, C., Hinz, M., Huber, K., Jürgens, N., Korn, E., Kowalski, B., Kralisch, S., Landschreiber, L., Lubinda, A., Luther-Mosebach, J., Maiato, F., Murray-Hudson, M., Pröpper, M., Reinhold, B., Revermann, R., Simfukwe, M., Stellmes, M., Stirn, S., Thito, K., Tsheboeng, G., Weber, T., Wehberg, J., Weinzierl, T., Zimmermann, I., 2015. Key findings and recommendations, in: Pröpper, M., Gröngröft, A., Finckh, M., Stirn, S., De Cauwer, V., Lages, F., Masamba, W., Murray-Hudson, M., Schmidt, L., Strohbach, B., Jürgens, N. (Eds.), The Future Okavango – Findings, Scenarios and Recommendations for Action. Research Project Final Synthesis Report 2010 — 2015. University of Hamburg, Hamburg, pp. 53–96.

Holt-Giménez, E. & Altieri, M.A. (2013) Agroecology, Food Sovereignty, and the New Green Revolution. *Agroecology and Sustainable Food Systems*, **37**, 90–102.

Nyirenda, V.R., Kaoma, C., & Nyirongo, S. (2018) Farmer-wildlife conflicts in rural areas of eastern Zambia. This volume. CrossRef

Ruthenberg, H., MacArthur, J. D., Zandstra, H. D. and Collinson, M.P. 1980. Farming systems in the tropics. Clarendon Press, New York

SADC Food Security Quarterly Update, March 2017

SADC Policy Paper on Climate Change: Assessing the Policy Options for SADC Member States 2012

Steward, P.R., Shackelford, G., Carvalheiro, L.G., Benton, T.G., Garibaldi, L.A. & Sait, S.M. (2014) Pollination and biological control research: are we neglecting two billion smallholders. *Agriculture & Food Security*, **3**, 5. CrossRef

The Namibian Newspaper, 22 June 2016: Namibia to roll out food bank programme.

The Namibia Newspaper, 2017 21 July 2017: Towards, the Peoples Land Conference.

Thierfelder C, Rusinamhodzi L, Ngwira AR, Mupangwa W, Nyagumbo I, Kassie GT and Cairns JE. 2013. Conservation agriculture in Southern Africa: Advances in Knowledge. Renewable Agriculture and Food Systems pp.1-21.

Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J., Whitbread, A., 2012. Global food security, biodiversity conservation and the future of agricultural intensification. Biol. Conserv. 151, 53–59. CrossRef

Von Braun J., Hazell P., Hoddinott J. and Babu S. 2003. Achieving long term food security in southern Africa: International perspectives, investment strategies and lessons. Key note paper prepared for the southern Africa regional conference on 'Agricultural recovery, trade and long-term food security', March 26- 27: Gaborone, Botswana.

Food security

Deforestation for agricultural expansion in SW Zambia and NE Namibia and the impacts on soil fertility, soil organic carbon- and nutrient levels

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Abstract: In southern African drylands, an important driver of deforestation is the ongoing conversion of woodland to smallholder agriculture. Our study in NE Namibia and SW Zambia evaluated the potential of operational earth observation satellites to characterize land-use change processes and quantified their impact on soil organic carbon (SOC) and nutrient concentrations. We found that the area under agricultural use increased by 24% from 2002 to 2013, mainly at the expense of natural vegetation (i.e., woodland). This conversion caused a decline in SOC and total N and tended to increase plant-available P in the soils of old agricultural fields. The effects were most pronounced in NE Namibia, where the total SOC stocks were 19.6% (±18.4 SD) lower in agricultural land compared to woodland. Moreover, the losses in SOC and total N tended to result in a decline of predicted maize yields calculated with the QUEFTS model by ~15% when comparing soils of old agricultural fields and woodland. Overall, our results indicate that long-term continuation of low-input arable farming can reduce soil fertility.

Resumo: Nas terras áridas da África Austral, a conversão contínua de floresta para agricultura de subsistência é um factor importante de desflorestação. O nosso estudo no Nordeste da Namíbia e Sudoeste da Zâmbia avaliou o potencial dos satélites operacionais de observação da Terra na caracterização dos processos de alteração do uso das terras e na quantificação dos seus impactos nas concentraçoes de nutrientes e de carbono orgânico no solo (SOC). Descobrimos que a área de uso agrícola aumentou em 24% entre 2002 e 2013, sobretudo à custa da vegetação natural (i.e. floresta). Esta conversão causou um declínio em SOC e N total, havendo uma tencência de aumento do P disponível para plantas nos solos de antigos campos agrícolas. Os efeitos foram mais pronunciados no Nordeste da Namíbia, onde as reservas de SOC totais eram 19,6% (±18.4 SD) mais baixas em terras agrícolas que em florestas. Além disso, as perdas de SOC e N total tenderam a resultar no declínio dos rendimentos previstos do milho calculados com o modelo QUEFTS em ~15%, quando comparados com solos de antigos campos agrícolas e florestas. No geral, os nossos resultados indicam que a continuação a longo prazo da agricultura arável de subsistência pode reduzir a fertilidade do solo.

Introduction

Agricultural expansion is among the main drivers of deforestation in southern Africa (Chomba et al., 2012; Kim et al., 2016). The demand for agricultural land is related to population growth in combination with diminishing soil nutrient levels and low-input arable cropping (Chomba et al., 2012). The majority of the rural population depends on agriculture for their food supplies and financial income (Pröpper et al., 2015). In these subsistence-farming systems, most farmers use little or no inputs of fertilizers or organic material, and crop yields strongly depend on the amounts of soil organic matter and soil nutrients. Farmers implement fallow periods when crop yields decline in order to restore soil fertility. Agricultural expansion is another way how farmers deal with declining yields or increasing food demand (Jayne et al., 2014; Stephenne & Lambin, 2001).

Remote sensing techniques can assist in monitoring agricultural expansion over long periods, as they provide an objective, repetitive, and consistent perspective across large areas. As such, time series of satellite images (for instance the Landsat mission that started in 1984) may contribute detailed information on land use, land cover, and corresponding changes and help to evaluate the impacts of human-driven processes on the environment (DeFries et al., 2004; Wulder et al., 2012). However, remote sensing–based analyses in the area at appropriate spatial resolutions are rare and partially outdated (e.g., Petit et al., 2001; Yang & Prince, 2000). The recent global analysis by Hansen et al. (2013) partially fills this gap, but it remains confined to forest/non-forest classes and operates on a definition of forests (>25% cover of trees taller than 5m) that fails to pick up many southern African woodlands.

The clearing of woodland for low-input arable cropping often leads to a decline in soil organic matter or soil organic carbon (SOC) and soil nutrient levels, as has been shown in pan-tropical reviews (Kleinman et al., 1995; Ribeiro Filho et al., 2015). The negative impacts on SOC levels were confirmed by the few published studies from semi-arid regions in sub-Saharan Africa (Demessie et al., 2013; Luther-Mosebach, 2017; Touré et al., 2013; Walker & Desanker, 2004). To our knowledge, there are no published studies for this region on the impacts of this land-use conversion on soil nutrient levels. Soil organic matter is important for crop productivity, as it improves the soil's cation exchange capacity, structure, and water-holding capacity. The negative impact of the woodland-to-agriculture conversion on soil organic matter and its primary component, SOC, may be related to various processes including the reduced input of organic material, soil erosion, and the accelerated decomposition of soil organic matter. The decline in soil nutrient levels is caused by loss in soil organic matter and by nutrient removal through crop harvesting (Kleinman et al., 1995). Additionally, burning of the plant biomass for woodland clearing affects soil nutrient levels. Although part of the nutrients in the plant biomass will be volatized, burning causes an input of nutrients to the soil from ash and fire residues (Juo & Manu, 1996). The ash produced is strongly alkaline and increases soil pH (Ribeiro Filho et al., 2015), which in turn accelerates microbial activity and increases soil nutrient availability (Giardina et al., 2000a). However, this effect may only be short term, as highly soluble nutrients such as K, Mg, and Ca may be lost by leaching (Juo & Manu, 1996).

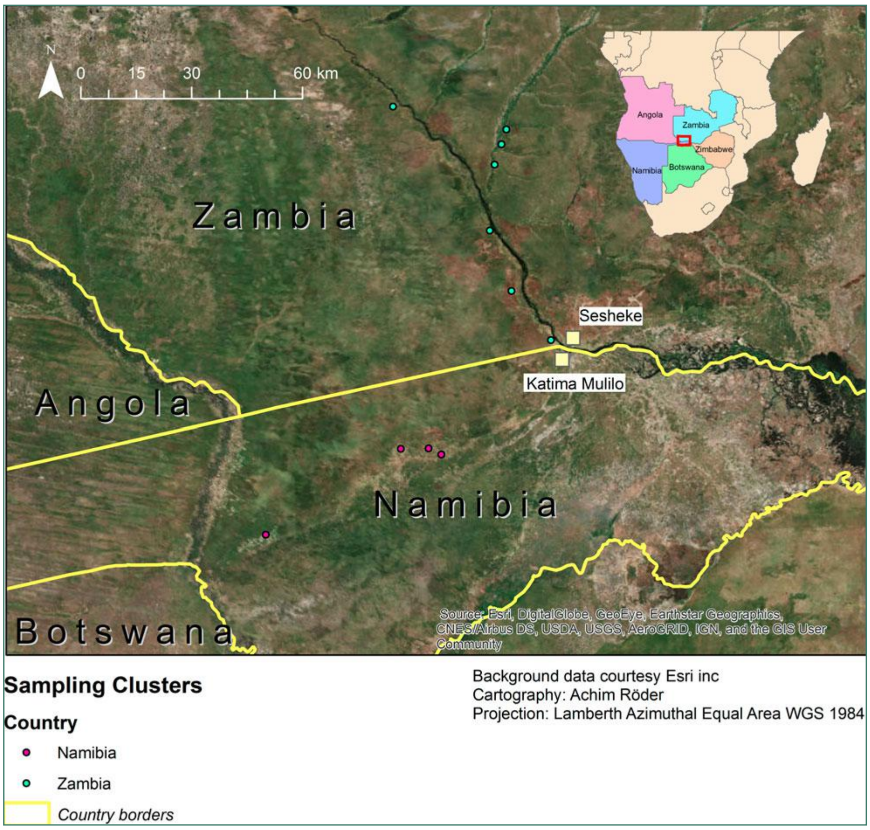

Figure 1: Overview of the study area and location of the sampling clusters. Note that within each cluster we sampled one to three agricultural fields and one plot in woodland.

Understanding the long-term impacts of low-input arable farming on the levels of soil nutrients and soil organic matter is necessary as a basis to develop strategies that may improve the crop yield of subsistence farmers. An approach that evaluates the combined impacts of soil pH and the levels of SOC and the macronutrients N, P, and K on yield is provided by the model Quantitative Evaluation of Fertility of Tropical Soils (QUEFTS) (Janssen et al., 1990; Sattari et al., 2014). QUEFTS is developed for tropical soils and applies a combination of empirical and theoretical relationships to calculate grain yields from chemical soil data. The predicted yields may serve as an indicator for soil fertility, and here soil fertility is defined as the soil's capacity to supply crops with N, P, and K (Janssen et al., 1990).

In this study, we focused on the conversion from woodland to low-input arable farming in the Zambezi region of NE Namibia and in the Sesheke District in SW Zambia. Our objectives were (1) to study the conversion from woodland to agriculture between 2002 and 2013 through a spatially explicit analysis using Landsat imagery, (2) to quantify the conversion-induced changes in soil nutrient concentrations and SOC concentrations and stocks in agricultural fields with an age up to 26 years (including fallow periods), and (3) to evaluate the conversion-induced changes in soil fertility by assessing the combined effects of soil pH, SOC, and soil nutrient concentrations on predicted crop yields.

Methods

Study areas

The study was conducted in the Kalahari Basin in the Zambezi region of NE Namibia and in the Sesheke District in SW Zambia. The land-use change detection analysis was done for a test area of ~317,770 km² (Fig. 1). The soil survey was conducted in two study areas within this test area; one was in NW Namibia located west of Katima Mulilo, and the other area was in Zambia located NW of Shesheke on the upper slope of the Zambezi River valley and its tributary (Fig. 1). The selection of the two study areas was based on a priori stratification by soil type according to SOTERSAF

(Dijkshoorn, 2003) and the *Soil Atlas of Africa* (Jones et al., 2013), and on the results of a land-use change detection analysis from Landsat imagery (see the paragraph "Land-use change detection"); we selected those areas where we identified the largest areas of agricultural expansion within the studied time frame.

Our field observations and laboratory results showed that the soil properties of the two areas differ in soil texture. The soils of the Namibian study area have a soil texture ranging from sandy loam to sand, are characterized by clay illuviation in the subsoil, and are classified as Haplic Luvisols or Dystric/Eutric- and/or Protoargic- Arenosols (IUSS Working Group WRB, 2014). In the Zambian area, the soils have a sandy soil texture that is uniform with depth and are classified accordingly as Arenosols with one or more of the principal qualifiers Brunic, Rubic, Eutric/Dystric. Soils in both areas have a wide range in pH (H_2O) from 4.7 to 7.4, which is independent of soil type, soil texture, or land use (Tab. 1).

The climate is hot semi-arid with a mean annual temperature of 20–22°C and a median annual precipitation of 550–600 mm (Mendelsohn et al., 2002). The majority of the precipitation is received between October and March. The topography in both study areas is relatively flat with no pronounced differences in altitude. The predominant tree species in the woodlands of the Namibian study area are *Colophospermum mopane* and *Schinziophyton rautanenii* and *Acacia* species. In the Zambian study area, most common tree species are *Schinziophyton rautanenii*, *Baikiaea plurijuga*, *Burkea africana,* and *Pterocarpus angolensis*. The main crops grown on the agricultural fields are beans, groundnuts, pearl millet, maize, and sorghum. According to the farmers, manure or other fertilizer are not applied on any of the investigated sampling plots. Fields are ploughed with draught animals once a year before sowing. To establish new agricultural fields, farmers typically convert woodland by cutting and subsequently burning the trees (Pröpper et al., 2015).

Table 1: Soil properties (means ± SD) of woodland (WL), old agricultural fields (OA), and young agricultural fields (YA) in two study areas in NE Namibia (NAM) and SW Zambia (ZAM).

Parameter	Depth (cm)	Study Area in Namibia			Study Area in Zambia		
		WL (*n* = 4)	YA (*n* = 6)	OA (*n* = 4)	WL (*n* = 7)	YA (*n* = 6)	OA (*n* = 7)
Bulk Density ($g\ cm^{-3}$)	0–10	1.41 (0.13)	1.48 (0.05)	1.45 (0.02)	1.49 (0.09)	1.51 (0.06)	1.54 (0.08)
	70–100	1.49 (0.03)	1.54 (0.05)	1.55 (0.07)	1.55 (0.03)	1.53 (0.03)	1.54 (0.05)
pH (H_2O)	0–10	6.24 (0.43)	6.34 (0.31)	6.17 (0.38)	5.93 (0.43)	6.28 (0.51)	6.08 (0.39)
	70–100	5.79 (1.2)	5.8 (0.48)	6.15 (0.2)	5.75 (0.29)	6.11 (0.55)	5.94 (0.43)
Phosphorus ($mg\ kg^{-1}$)	0–10	0.25 (0.06)	0.44 (0.34)	0.97 (1.33)	6.17 (2.19)	7.53 (3.19)	5.43 (1.82)
Total N (%)	0–10	0.06 (0.006)	0.04 (0.009)	0.03 (0.007)	0.06 (0.015)	0.06 (0.029)	0.04 (0.01)
	70–100	0.02 (0.004)	0.02 (0.002)	0.02 (0.002)	0.02 (0.002)	0.01 (0.002)	0.02 (0.002)
SOC (%)	0–10	0.69 (0.1)	0.49 (0.14)	0.36 (0.08)	0.74 (0.25)	0.73 (0.34)	0.43 (0.13)
	70–100	0.21 (0.02)	0.19 (0.02)	0.18 (0.03)	0.12 (0.04)	0.12 (0.05)	0.11 (0.02)
SOC Stocks ($Mg\ C\ ha^{-1}$)	0–100	47.9 (2.2)	40.1 (4.3)	39.3 (7.2)	37.2 (8.8)	39.1 (11.0)	31.4 (5.6)
Exchangeable K ($mg\ kg^{-1}$)	0–10	110 (33.43)	130.43 (51.72)	101.58 (27.69)	41.89 (12.98)	34.67 (9.41)	48.84 (20.39)

Land-use change detection

To detect land-use changes we classified the land use in a test area of ~317,770 km² (one Landsat full frame, path 174/172) from Landsat images acquired in the 2002 period and in 2013 representing the recent state. We made use of a Landsat archive that provides all existing images until 2015 processed to surface reflectance (Frantz et al., 2016; Röder et al., 2018). By selecting multi-temporal datasets for each of the studied years (9/4/2002, 30/7/2002, 18/10/2002, and 15/4/2013, 20/7/2013, 8/10/2013), we incorporated the phenological variability of the different surfaces through a climatic season. All images were stacked to form 18-band layers for the 2002 and 2013 periods, respectively. Information on the most distinct land-use classes was based on a supervised classification using the maximum likelihood classifier, which assigns class membership based on the highest probability of class membership by comparing the respective pixel to a set of training pixels (Richards, 2013). Target classes were settlements, agricultural areas, bare areas, sparse vegetation, forests, water, and wetlands. In addition, areas recently affected by fires were differentiated. Using high-resolution imagery (e.g., Google Earth™ and Bing Maps™) and a visual analysis of the Landsat data, we selected an average of 60 reference points for each class to train the classifier. Since no corresponding high-resolution data were available to derive training data for the previous date, we propagated the training dataset to the historic dataset using band- and date-wise differences between corresponding recent and historic images (and bands). Since, independently of surface type, spectrally stable features can be assumed to have unchanged reflectance, we could identify these using thresholds and use the respective land use information derived for the recent date to parameterize the classifier for the earlier period. For both periods, the agricultural and settlement classes showed overlaps with vegetation classes; therefore, for these classes an unsupervised classification with manual attribution was additionally carried out. Furthermore, we calculated the tasselled cap coefficients for all images (Kauth & Thomas, 1976), which decompose images into "brightness", "greenness" and "wetness" components using a linear transformation based on predefined coefficients. Thus, the discrete vegetation classes could be replaced by continuous fields represented by the "greenness" fraction for different periods for maps, while discrete classes were used together with 591 independent points identified in Google Earth™ and Bing Maps™ for validation using a stratified random sampling. We used the results from the land-use change analysis to stratify the test area into areas that were largely affected by the woodland-to-agriculture conversion (i.e., agricultural expansion) and used this information to select our two study areas for the soil survey.

Sampling design

In the two study areas we selected a total of 11 sampling clusters, four in Namibia and seven in Zambia. Each sampling cluster had a 1 km radius in which we selected up to three sampling plots in agriculture and one plot in woodland. We selected the clusters by stratified random sampling as follows: First, based on the results from the discrete change detection, we stratified the two study areas into woodland (classified as natural vegetation), young (classified as agriculture since 2013) and old agricultural fields (classified as agriculture from both 2002 and 2013 imagery), and others. Second, within each study area, we randomly selected clusters within a 5 km distance from a road in from areas that contained both woodland and agriculture. Finally, in the field, the sampling plots within a cluster were carefully selected to have similar topographic and soil characteristics. To verify the age of the selected agricultural fields, we used the information from farmers and a time series from 1987 to 2014 of the Enhanced Vegetation Index (EVI) derived from Landsat satellite images. By visual comparison of EVI time series of agricultural and woodland plots, we were able to determine the first year of agricultural usage. Moreover, the EVI data showed that most sampling plots after original conversion have rested for some growing seasons. Thus, the ages of the agricultural fields used in this study are based on the first year of agricultural usage and should be interpreted as total agricultural duration that may include a sequence of cropping and fallow periods. The agricultural plots classified as young fields ranged in age from 2 to 12 years and the old fields from 13 to 26 years. In the Namibian study area, we sampled four plots in woodlands, six in young agricultural fields, and four in old agricultural fields, and in the Zambian study area seven in woodlands, six in young agricultural fields, and seven in old agricultural fields.

Soil sampling and laboratory analysis

Sampling plots had a size of 30 m x 30 m. A soil pit was dug in the plot centre. We took soil samples for chemical and physical property analyses from five depth intervals down to 100 cm: 0–10 cm, 10–20 cm, 20–40 cm, 40–70 cm and 70–100 cm. Additionally, soil samples of the upper three depths were taken with an Edelmann auger from 12 points that were situated at a distance of 5 m, 10 m, and 15 m from the plot centre in each of the four cardinal directions. We mixed these samples in the field to form one pooled sample per depth and plot. All soil samples were collected in November 2015. Sieved soil samples (<2 mm) were analysed for pH (H_2O), bulk density, SOC, total N, exchangeable K, and plant-available P. Soil pH (H_2O) was measured with a pH electrode in soil suspensions with a 1:2.5 soil-to-water ratio. Soil bulk density was measured using the core method (Blake & Hartge, 1986). The bulk density samples did not contain stones or coarse fragments >2 mm, so we did not correct for gravel content. Soil carbon and nitrogen concentrations were measured on ground samples by dry combustion using an elemental analyzer (varioMAX, elemental analyzer). As soil pH was below pH 7, carbonates were not expected and total carbon was assumed to equal SOC. Exchangeable potassium was extracted with ammonium acetate. The extracted cations were quantified by atomic absorption and atomic emission spectroscopy (Helmke & Sparks, 1996). We extracted plant-available P (P-Olsen) with a buffered alkaline solution according to Kuo (1996).

Calculations and statistical analysis

SOC stocks in each depth interval were calculated by:

$$SOC\ (\mathrm{Mg\ C\ ha^{-1}}) = \frac{\%\,C}{100} \times BD\ (Mg\ m^{-3}) \times \Delta\mathrm{D}\ (m) \times 10{,}000\ m^2 ha^{-1}$$

where BD is the soil bulk density and ΔD is the thickness of the sampling depth. Total SOC stocks to a 100 cm depth were calculated as the sum over all depths. The comparisons of SOC stocks among the studied land-use types were based on equivalent soil masses (Ellert & Bettany, 1995) to account for possible alterations in soil bulk density with land-use change. In our calculations of SOC stocks, it was not necessary to correct for the proportion of rocks in the soil profile, since the profiles were free of rocks and the BD samples did not contain coarse fragments >2 mm.

To assess the soil fertility of the plots, we used the QUEFTS model (Janssen et al., 1990; Sattari et al., 2014). Using QUEFTS we predicted maize yields from our data on soil pH and concentrations of SOC, exchangeable K, total N, and plant-available P to 20 cm depth. We chose to predict maize yields since, of the crops grown in the region, it is the only crop included in the model. QUEFTS estimates crop yields under the assumption that N, P, and K are the only growth-limiting factors. Maize yields are calculated in four steps: (1) Calculation of the potential supply of N, P, and K based on empirically derived equations between soil chemical data and maximum nutrient uptake when no other nutrients or growth factors are yield limiting. We assumed no additional fertilizer input. (2) Quantification of the actual nutrient uptake from theoretical trends between potential nutrient supply and actual uptake. (3) Calculation of three yield ranges from the actual uptake of N, P, and K, respectively, with empirically derived equations for nutrient limiting and nonlimiting conditions. (4) Estimation of a final yield by combining the yield ranges calculated in step 3.

Statistical analyses were done in the statistical software R version 3.3.3 (R Core Team, 2017). To test whether agriculture and woodland in each cluster differed in SOC and nutrient contents

Table 2: Confusion matrix and accuracy assessment showing the agreement between the results of the land-use classification from Landsat data and class assignments derived from high-resolution imagery for 591 validation points (based on stratified random sampling), overall accuracy 0.795 (confidence interval 0.051).

		Reference Points									
		Woodland	Sparse Vegetation	Bare ground	Agriculture	Settlement	Seasonally Flooded	Water	SUM	User's Accuracy (UA)	UA Confidence Interval
Classification	Woodland	**26**	29	0	0	1	3	0	**59**	0.441	0.128
	Sparse Vegetation	8	**249**	10	0	0	2	0	**269**	0.926	0.031
	Bare ground	0	21	**34**	0	0	0	0	**55**	0.618	0.13
	Agriculture	1	12	7	**32**	0	0	0	**52**	0.615	0.134
	Settlement	0	8	6	7	**31**	0	0	**52**	0.596	0.135
	Seasonally Flooded	0	1	0	0	0	**50**	1	**52**	0.962	0.053
	Water	0	0	0	0	0	4	**48**	**52**	0.923	0.073
SUM		**35**	**320**	**57**	**39**	**32**	**59**	**49**	**591**		
Producer's Accuracy (PA)		0.939	0.328	0.826	0.949	0.846	0.894	0.888			
PA Confidence Interval		0.056	0.042	0.079	0.035	0.257	0.088	0.195			

and stocks, soil pH, and predicted maize yields, we used linear mixed effects models (LME) using the nlme package (Pinheiro et al., 2012). Response variables were the selected soil properties or predicted maize yields, and cluster was included as a random factor. We included land-use type, study area, and the interaction between land-use type and study area as fixed effects. If the interaction term was not significant, we continued with a model without interaction. Post-hoc tests (Tukey's test from the lsmeans package [Lenth, 2016]) were performed for multiple comparisons between land-use types and study areas.

Results

Land-use change detection

Following the methodology suggested by Olofsson et al. (2014), classification accuracies for the recent date (2013) were validated using a stratified random sample approach with a total of 591 validation points and corresponding high-resolution imagery (Google Earth™), with a kappa index of 0.71 and an overall accuracy of 79.5 %. Difficulties were encountered mainly in highly heterogeneous areas with intricate mixtures of small agricultural plots, rural settlements constructed mainly of natural materials, and bare areas, which are spectrally highly similar and where the absence of peak wet-season imagery means many fields are not recorded under fully cropped conditions.

Similarly, threshold-based differentiation of denser vegetation (class "forest") from less dense vegetation (class "open vegetation") caused some confusion (compare Tab. 2), which may be avoided by inserting density classes (tasselled cap greenness). However, distinguishing naturally vegetated areas from human-appropriated land as the basis for subsequent analyses was successful. For visualization purposes, we aggregated classes to five overarching categories: vegetation, bare, anthropogenic, water, and fire affected, where the latter includes pixels that were mapped as recently burned on one of the dates. Figure 2 illustrates the change processes during the investigation period.

By comparing the discrete classifications of 2002 and 2013, we were able to identify a net increase of agriculturally used areas by approximately 430 km² (+24%) between 2002 and 2013, added to by an increase in settlement area of 197 km² (+55%, Fig. 2). Mostly as a result

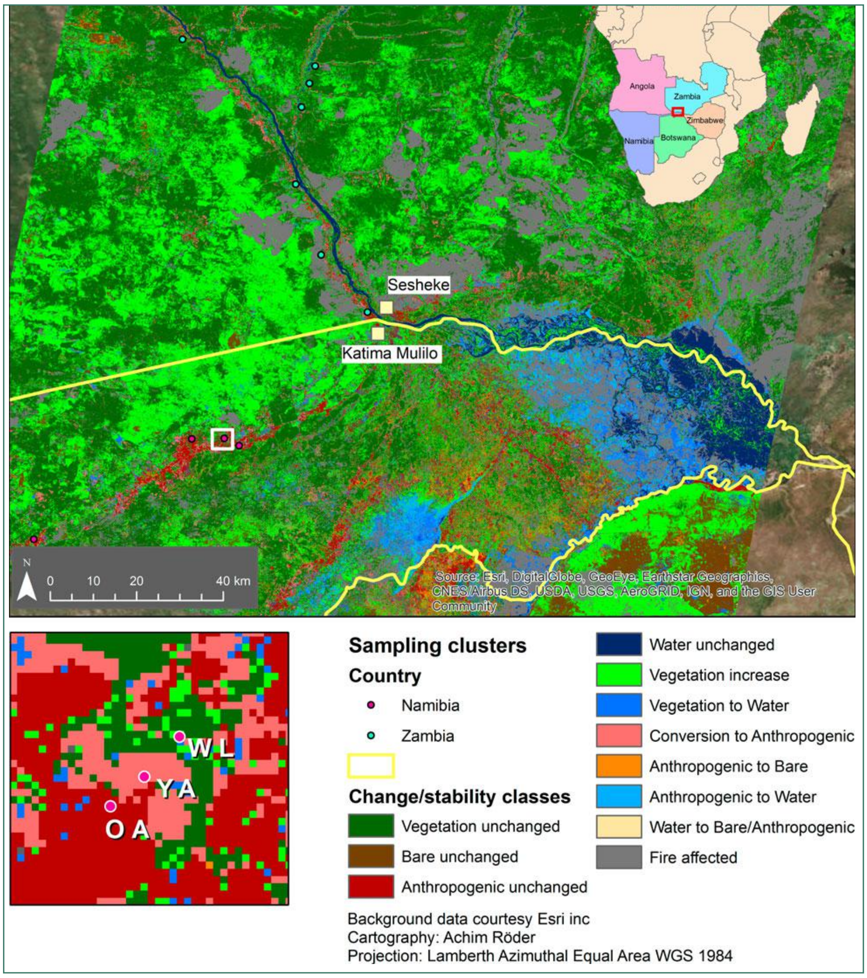

Figure 2: Change map summarizing major change processes between 2002 and 2013. The zoom subset corresponds to the white frame in the main map and illustrates placement of ground sampling points (WL = woodland, YA = young agricultural field, and OA = old agricultural field) for one sampling cluster.

of several preceding years of high precipitation, a significant increase in both surface water (226 km^2, 224%) and seasonal flooding (1,143 km^2, 107%) was observed. The increase of the anthropogenic class (cropland, settlement) was mainly at the expense of natural vegetation, while a number of previously existing fields were lost because of the expansion of water and flooded areas. Additional analyses of the location of the agricultural fields with auxiliary data showed their concentration next to newly created roads and settlements. The results of the classification appeared useful for selection of the sampling clusters for the following soil survey.

Differences in soil organic carbon and soil nutrient concentrations between woodland and agriculture

Compared to woodland, old agricultural fields had lower concentrations of total N ($p < 0.001$) and SOC ($p < 0.001$) in the topsoil (0–10 cm depth, Fig. 3a and Fig. 3d) in both study areas. Woodland had the largest element concentrations, followed by young agricultural fields and old agricultural fields (Tab. 1). However, the differences in total N and SOC between young agricultural fields and woodland were nonsignificant. Despite the difference in SOC concentrations between young and old agricultural fields ($p = 0.03$), we observed no significant difference in N concentrations between these land-use types. Comparing total SOC stocks down to 100 cm depth showed that woodlands had higher SOC stocks compared to young ($p = 0.02$) and old agricultural fields ($p = 0.01$) in the Namibian study area (Tab. 1 and Fig. 3e). The mean difference (agriculture minus woodland) in SOC stocks revealed a loss of 9.6 (± 8.9 SD) Mg C ha^{-1} (relative loss of 19.6 ± 18.4 SD %), with differences ranging from losses of 18.5 Mg C ha^{-1} (relative loss of 38.6%) to 0.9 Mg C ha^{-1} (relative loss of 1.9%). The difference in SOC stocks between young and old agricultural fields in this study area was not significant. For the study area in Zambia, we did not observe significant differences in total SOC stocks between woodland and agriculture. However, SOC stocks in old agricultural fields were lower compared to those in young fields ($p = 0.02$). Plant-available P and exchangeable K concentrations did not significantly differ between agriculture and woodland in either study area (Tab. 1, Fig. 3b and Fig. 3c). However, the majority of the sampled agricultural fields in both study areas had higher plant-available P concentrations compared to woodland, and the majority of sampled soils of young agricultural fields in the Namibian study area had higher exchangeable K concentrations than did woodland soil.

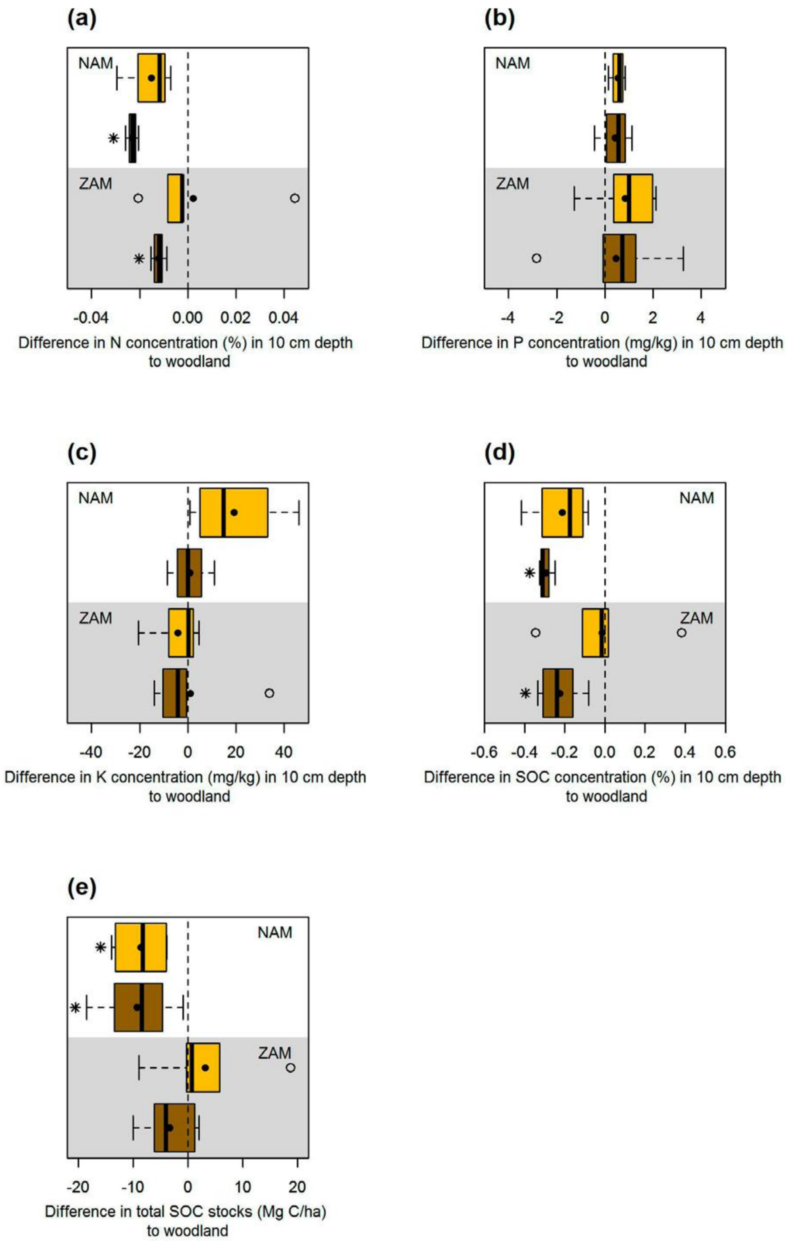

Figure 3: Difference of young agricultural fields (yellow box) and old agricultural fields (brown box) to woodland (agriculture minus woodland) in concentrations (%) of N (a), P (b), K (c), and SOC (d) in the topsoil (0–10 cm) and in total SOC stocks (Mg C ha-1) to 100 cm depth (e) in NE Namibia (NAM) and SW Zambia (ZAM). In the boxplots, the box shows the 25th and 75th percentiles, the median (black line), the mean (black dot), and outliers (circles), and the whiskers extend to the data extremes that do not exceed 1.5 times the interquartile range. Asterisks show significant differences between agriculture and woodland ($p < 0.05$, LME models and Tukey's test).

Predicted maize yields

The maize yields estimated with QUEFTS ranged from 470 kg ha^{-1} to 1,300 kg ha^{-1} (Tab. 3) and did not statistically differ between soils of woodland and young or old agricultural fields in either study area, nor did the predicted yields differ between the study areas. However, the maize yields predicted for old agricultural fields tended to be 15.2% (SD 28.2%) lower than those for woodland in both study areas ($p = 0.07$). Moreover, in the

Table 3: Predicted maize yields (means ± SD) calculated with the QUEFTS model (Janssen et al., 1990) for soils of woodland (WL), young agricultural fields (YA), and old agricultural fields (OA); differences in potential maize yields between the soils of each land-use type per study area (NAM in NE Namibia and ZAM in SW Zambia); and the soil nutrients indicated to be yield limiting.

Study Area	Predicted Maize Yield (kg ha^{-1})			Differences in Maize Yields (kg ha^{-1}) between Land-Use Types			Yield-Limiting Nutrients		
	WL (*n* = 4 for NAM, *n* = 7 for ZAM)	YA (*n* = 6 for NAM, *n* = 6 for ZAM)	OA (*n* = 4 for NAM, *n* = 7 for ZAM)	OA-WL (*n* = 3 for NAM, *n* = 5 for ZAM)	YA-WL (*n* = 4 for NAM, *n* = 5 for ZAM)	OA-YA (*n* = 4 for NAM, *n* = 3 for ZAM)	WL (*n* = 4 for NAM, *n* = 7 for ZAM)	YA (*n* = 6 for NAM, *n* = 6 for ZAM)	OA (*n* = 4 for NAM, *n* = 7 for ZAM)
NAM	1,017 (104)	908 (255)	744 (256)	–333 (189)	–119 (82)	–208 (104)	P (*n* = 4)[a]	N (*n* = 3), P (*n* = 3)	N (*n* = 3), P (*n* = 1)
ZAM	945 (239)	924 (231)	784 (158)	–77 (189)	–27 (254)	63 (228)	N (*n* = 6), K (*n* = 1)	N (*n* = 5), K (*n* = 1)	N (*n* = 6), P (*n* = 1)

[a] *n* indicates the number of sampling plots for which the given nutrient is yield limiting.

Namibian study area, we predicted lower yields for five of the six young agricultural plots than for woodland. QUEFTS indicated that in the Namibian study area, P was the element that was most limiting plant growth in eight sampling plots; in the other six plots, N was the yield-limiting element (Tab. 3). In the Zambian area, for all except three sampling plots N was the element that limited maize yield.

Discussion

Land-use change detection

We applied a hybrid classification methodology comprising a maximum likelihood–based classification and the calculation of a tasselled cap transformation to evaluate change processes in one Landsat full frame. Difficulties in class assignment resulted primarily from known effects in rural, savannah-type systems with distinct wet and dry season cycles. A lack of wet-season imagery and the utilization of natural building materials often result in spectral ambiguities and make it hard to distinguish settlements, bare ground, and agricultural plots; similarly, differentiation of vegetation in discrete cover classes is complicated as a result of strong inter-annual variations.

However, the ability to distinguish between natural and human-dominated classes overall was found to be reliable and allowed for a stratification of the subsequent ground-based soil analyses. Our results confirm the conversion of woodland to agricultural or settlement areas as the dominant conversion process, and spatial analyses indicating the proximity to roads or other settlements as a major determinant agree with similar studies (e.g., Röder et al., 2015). Of particular interest is the impact of precipitation patterns preceding the 2013 period, which caused the significant extension of seasonal flooding areas and of Lake Liambezi, with an associated disappearance of all agricultural fields that had still been there in the earlier period. Again, this is a temporal phenomenon with process length corresponding to mid-term precipitation variation, and which might be better resolved using continuous time series (see for instance Schneibel et al., 2018).

Impact of land-use change on soil organic carbon concentrations and stocks

Our findings of reduced SOC concentrations and stocks (Fig. 3d and Fig. 3e) in low-input agriculture following the conversion from woodland is typical (Ribeiro Filho et al., 2015; Walker & Desanker, 2004). The observed total SOC stock losses (100 cm depth) in the Namibian study area, which ranged from 38.6% to 1.9% with an average loss of 19.6% (±18.4 SD), correspond well with the losses reported by the few other studies on the conversion to low-input agriculture in the semi-arid ecosystems of sub-Saharan Africa (Demessie et al., 2013; Luther-Mosebach, 2017; Touré et al., 2013; Walker & Desanker, 2004). A chronosequence study on an Andic Paleustalfs in southern Ethiopia showed that the conversion from forest to agriculture and agroforestry reduced SOC stocks by 12% to 43% after 12 to 50 years of cultivation (Demessie et al., 2013). In central Senegal on Luvisols and Arenosols, total SOC stocks were 27% to 37% lower in groundnut fields with an age up to 25 years compared to savannahs (Touré et al., 2013). On Ferralsols in central Malawi (Walker & Desanker, 2004), SOC stocks were 40% lower in agricultural fields with a maximum age of 30 years than in miombo woodlands. In NE Namibia, Luther-Mosebach (2017) also reported lower SOC stocks in old agricultural fields compared to woodland, with differences in SOC stocks between agriculture and woodland being a maximum of 39%. Nevertheless, they observed little to no differences between woodland and slash-and-burn agriculture. All the above-listed losses in SOC stock have been reported for a soil depth of 100 cm. Possible reasons for the SOC losses are the reduced inputs of organic material in agricultural soils and enhanced mineralization rates as a result of soil disturbances from tillage. Burning of woodland may also have affected SOC levels by charcoal inputs, thermally induced SOC losses, and soil-heating effects on the chemical composition of soil organic matter. There is no consensus across studies, however, on the direction of fire effects on SOC levels (Eckmeier et al., 2007; Fynn et al., 2003).

Impact of land-use change on soil nutrient concentrations

The observed decline in total soil N concentrations in old agricultural fields following the conversion from woodland

(Fig. 3a) is consistent with the literature (Demessie et al., 2013; Giardina et al., 2000a; Ribeiro Filho ss, 2015). The decreases in total N are parallel to the SOC losses, which is typical, as the dynamics of both organic N and SOC are linked to the decomposition of soil organic matter. Crop harvesting without nutrient returns through fertilization may also have contributed to the N losses (Giller et al., 1997). Moreover, fire-related N losses due to volatilization and leaching, and limited N inputs from ash may have played a role. The N inputs from ash are generally low, as large proportions of N volatilize during biomass burning (Giardina et al., 2000a). Moreover, soil heating may volatize part of the soil N and may transform non-plant-available N into mineral N readily available to plants (Giardina et al., 2000b), which is easily lost by plant uptake and leaching during rain events.

Though it was not statistically significant, in both study areas plant-available P increased in old and young agricultural fields (Fig. 3e), and exchangeable K concentrations increased in young agricultural fields in the Namibian study area; this tendency may be related to P and K fertilization from ash input caused by biomass burning (Giardina et al., 2000a,b). Increases in plant-available P after biomass burning could, besides ash fertilization, be related to mineralization from organic P. Plant uptake and the fact that K is highly soluble (Juo & Manu, 1996) may explain why we did not observe an increase in K concentrations in old agricultural fields. Similar to our results, Wallenfang et al. (2015) observed an increase in soil K in young fields, but a decline with extended duration of agricultural use after slash-and-burn in SE Angola.

Impact of land-use change on predicted maize yield

The trend (not statistically significant) of lower predicted maize yields for old agricultural fields than for woodland (Tab. 3) indicates that soil fertility may decline with the long-term continuation of low-input arable farming. The decrease in predicted maize yields on the majority of the sampled old agricultural fields corresponds with the observed losses in SOC and total N concentrations for this land-use type (Fig. 3a and Fig. 3d). Our maize yields that ranged from 470 kg ha^{-1} to 1,300 kg ha^{-1} were in line with predictions by Pröpper et al. (2015), who predicted potential maize yields between 800 and 1,200 kg ha^{-1} for soils in the Kavango region that were selected by farmers as preferential for agricultural use. Yield data from field measurements on sandy soils in the region are hard to find; the only published study that we found reported average maize yields of 500 kg ha^{-1} for nonfertilized field trials on aeolian sands in western Zambia (Cornelissen et al., 2013). The predictions by QUEFTS most likely overestimate actual yields, as QUEFTS does not consider the impacts of soil water availability and management practices (Tittonell et al., 2008). As is typical for sandy soils of the semi-arid tropics (Buresh et al., 1997; Giller et al., 1997), we found that soil N and soil P were the main yield-limiting nutrients (Tab. 3). Our result that soil P was yield limiting in half of the sampling plots in Namibia whereas in Zambia soil P was only yield limiting in one sampling plot, corresponds with the much lower concentrations of soil P in the Namibian study area compared to the Zambian study area (Tab. 1).

Conclusion

We found that between 2002 and 2013 the area under agricultural use increased by 24%, mainly at the expense of natural vegetation (i.e., woodland). This land-use conversion resulted in losses in SOC and total N and tended to increase of plant-available P. The SOC losses were most pronounced in the Namibian study area, where SOC stocks were reduced by 9.6 Mg C ha^{-1} (~20%) over a depth of 100 cm. Furthermore, our findings show that long-term agricultural use tends to reduce soil fertility; predicted maize yields declined by ~15% (average for both study areas) when comparing soils of old agricultural fields and woodland, this reduction is attributable to the observed losses in SOC and total N.

Results from our remote sensing analyses showed that even in areas with heterogeneous patterns of land use, in particular in areas dominated by small-scale agriculture, broad change patterns may reliably be identified and used to stratify subsequent analyses. We showed that classic change analysis is a suitable tool to achieve this, whereas more enhanced methods, such as the recently developed CAT transformation (Frantz et al., 2017; Hird et al., 2016) would be well suited to illustrate more subtle processes by making use of full time series rather than a limited number of dates. Furthermore, combining remote sensing techniques to detect land-use changes followed by the selection of sampling clusters with stratified random sampling and field sampling has the advantage that it enables the extrapolation of change effects over entire landscape units.

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References

Blake, G.R. & Hartge, K.H. (1986) Bulk density. *Methods of soil analysis, part 1: Physical and mineralogical methods* (ed. by A. Klute), pp. 363–375. Soil Science Society of America, Madison, WI.

Buresh, R.J., Smithson, P.C. & Hellums, D.T. (1997) Building soil phosphorus capital in Africa. *Replenishing soil fertility in Africa* (ed. by R.J. Buresh, P.A. Sanchez, & F. Calhoun), pp. 111–149. Soil Science Society of America and American Society of Agronomy, Madison, WI.

Chomba, B.M., Tembo, O., Mutandi, K., Mtongo, C.S. & Makano, A. (2012) *Drivers of deforestation, identification of threatened forests and forest co-benefits other than carbon from REDD+ implementation in Zambia.* Ministry of Lands, Natural Resources and Environmental Protection, Lusaka, Zambia.

Cornelissen, G., Martinsen, V., Shitumbanuma, V., Alling, V., Breedveld, G., Rutherford, D., Sparrevik, M., Hale, S., Obia, A. & Mulder, J. (2013) Biochar effect on maize yield and soil characteristics in five conservation farming sites in Zambia. *Agronomy*, **3**, 256–274.

DeFries, R.S., Foley, J.A. & Asner, G.P. (2004) Land-use choices: Balancing human needs and ecosystem function. *Frontiers in Ecology and the Environment*, **2**, 249–257.

Demessie, A., Singh, B.R. & Lal, R. (2013) Soil carbon and nitrogen stocks under chronosequence of farm and traditional agroforestry land uses in Gambo District, Southern Ethiopia. *Nutrient Cycling in Agroecosystems*, **95**, 365–375.
Dijkshoorn, J.A. (2003) *SOTER database for Southern Africa (SOTERSAF).* ISRIC-World Soil Information, Wageningen, the Netherlands.
Eckmeier, E., Gerlach, R., Skjemstad, J.O., Ehrmann, O. & Schmidt, M.W.I. (2007) Minor changes in soil organic carbon and charcoal concentrations detected in a temperate deciduous forest a year after an experimental slash-and-burn. *Biogeosciences*, **4**, 377–383.
Ellert, B.H. & Bettany, J.R. (1995) Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Canadian Journal of Soil Science*, **75**, 529–538.
Frantz, D., Röder, A., Stellmes, M. & Hill, J. (2016) An operational radiometric Landsat preprocessing framework for large-area time series applications. *IEEE Transactions on Geoscience and Remote Sensing*, **54**, 3928–3943.
Fynn, R.W.S., Haynes, R.J. & O'Connor, T.G. (2003) Burning causes long-term changes in soil organic matter content of a South African grassland. *Soil Biology and Biochemistry*, **35**, 677–687.
Giardina, C., Sanford, R., Døckersmith, I. & Jaramillo, V. (2000a) The effects of slash burning on ecosystem nutrients during the land preparation phase of shifting cultivation. *Plant and Soil*, **220**, 247–260.
Giardina, C.P., Sanford Jr., R.L. & Døckersmith, I.C. (2000b) Changes in soil phosphorus and nitrogen during slash-and-burn clearing of a dry tropical forest. *Soil Science Society of America Journal*, **64**, 399–405.
Giller, K.E., Cadisch, G., Ehaliotis, C., Adams, E., Sakala, W.D. & Mafongoya, P.L. (1997) Building soil nitrogen capital in Africa. *Replenishing soil fertility in Africa* (ed. by R.J. Buresh, P.A. Sanchez, & F. Calhoun), pp. 151–192. Soil Science Society of America and American Society of Agronomy.
Hansen, M.C., Potapov, P. V., Moore, R. et al. (2013) High-resolution global maps of 21st-century forest cover change. *Science*, **342**, 850–854.
Helmke, P.A. & Sparks, D.L. (1996) Lithium, sodium, potassium, rubidium, and cesium. *Methods of soil analysis, part 3: Chemical methods* (ed. by D.L. Spartks), pp. 551–574. Soil Science Society of America, Inc., Madison, WI.
Hird, J.N., Castilla, G. McDermid G.J.B., Bueno, I.T. (2016) A simple transformation for visualizing non-seasonal landscape change from dense time series of satellite data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **9**, 3372-3383.
IUSS Working Group WRB (2014) *World reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps.* World Soil Resources Reports No. 106. FAO, Rome.
Janssen, B.H., Guiking, F.C.T., Van der Eijk, D., Smaling, E.M.A., Wolf, J. & Van Reuler, H. (1990) A system for quantative evaluation of the fertility of tropical soils (QUEFTS). *Geoderma*, **46**, 299–318.
Jayne, T.S., Chamberlin, J. & Headey, D.D. (2014) Land pressures, the evolution of farming systems, and development strategies in Africa: A synthesis. *Food Policy*, **48**, 1–17.
Jones, A., Breuning-Madsen, H., Brossard, M. et al. (2013) *Soil atlas of Africa*. European Commission, Publications Office of the European Union, Luxembourg.
Juo, A.S.R. & Manu, A. (1996) Chemical dynamics in slash-and-burn agriculture. *Agriculture, Ecosystems and Environment*, **58**, 49–60.
Kauth, R.J. & Thomas, G. (1976) The tasselled cap--A graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. *LARS Symposia*, p. 159.
Kim, D.G., Thomas, A.D., Pelster, D., Rosenstock, T.S. & Sanz-Cobena, A. (2016) Greenhouse gas emissions from natural ecosystems and agricultural lands in sub-Saharan Africa: Synthesis of available data and suggestions for further research. *Biogeosciences*, **13**, 4789–4809.
Kleinman, P.J.A., Pimentel, D. & Bryant, R.B. (1995) The ecological sustainability of slash-and-burn agriculture. *Agriculture, Ecosystems & Environment*, **52**, 235–249.
Kuo, S. (1996) Phosphorous. *Methods of soil analysis, part 3* (ed. by D.L. Sparks), pp. 869–919. SSSA Book Series 5. Soil Science Society of America, Inc., Madison, WI.
Lenth, R.V. (2016) Least-squares means: The R package lsmeans. *Journal of Statistical Software*, **69**, 1–33.
Luther-Mosebach, J. (2017) *Soil carbon stocks and dynamics in soils of the Okavango Catchment*, vol. 89. Hamburger Bodenkundlichen Arbeiten, Hamburg, Germany.
Mendelsohn, J., Jarvis, A., Roberts, C. & Robertson, T. (2002) *Atlas of Namibia: A portrait of the land and its people*. David Philip Publishers, Cape Town, South Africa.
Olofsson, P., Foody, G.M., Herold, M., Stehman, S.V., Woodcock, C.E. & Wulder, M.A. (2014) Good practices for estimating area and assessing accuracy of land change. *Remote Sensing of Environment*, **148**, 42–57.
Petit, C., Scudder, T. & Lambin, E. (2001) Quantifying processes of land-cover change by remote sensing: Resettlement and rapid land-cover changes in south-eastern Zambia. *International Journal of Remote Sensing*, **22**, 3435–3456.
Pinheiro, J., Bates, D., DebRoy, S., Sarker, D. & R Core Team (2012) *nlme: Linear and nonlinear mixed effects models.* R package version 3.1-131. https://cran.r-project.org/package=nlme
Pröpper, M., Gröngröft, A., Finckh, M., Stirn, S., Cauwer, V. De, Lages, F., Masamba, W., Murray-Hudson, M., Schmidt, L., Strohbach, B. & Jürgens, N. (2015) *The future Okavango – Findings, scenarios and recommendations for action*. Hamburg, Germany.
R Core Team (2017) *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/
Ribeiro Filho, A.A., Adams, C., Manfredini, S., Aguilar, R. & Neves, W.A. (2015) Dynamics of soil chemical properties in shifting cultivation systems in the tropics: A meta-analysis. *Soil Use and Management*, **31**, 474–482.
Richards, J.A. (2013) *Remote sensing digital image analysis*. Springer, Berlin.
Röder, A., Pröpper, M., Stellmes, M., Schneibel, A. & Hill, J. (2015) Assessing urban growth and rural land use transformations in a cross-border situation in Northern Namibia and Southern Angola. *Land Use Policy*, **42**, 340–354.
Röder, A., Stellmes, M., Frantz, D. & Hill, J. (2018) Remote sensing-based environmental assessment and monitoring – generation of operational baseline and enhanced experimental products in southern Africa. This volume.
Sattari, S.Z., van Ittersum, M.K., Bouwman, A.F., Smit, A.L. & Janssen, B.H. (2014) Crop yield response to soil fertility and N, P, K inputs in different environments: Testing and improving the QUEFTS model. *Field Crops Research*, **157**, 35–46.
Schneibel, A., Röder, A., Stellmes, M. & Frantz, D. (2018) Long-term land use change analysis in south-central Angola. Assessing the trade-off between major ecosystem services with remote sensing data. This volume.
Stephenne, N. & Lambin, E. (2001) A dynamic simulation model of land-use changes in Sudano-Sahelian countries of Africa (SALU). *Agriculture, Ecosystems & Environment*, **85**, 145–161.
Tittonell, P., Vanlauwe, B., Corbeels, M. & Giller, K.E. (2008) Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. *Plant and Soil*, **313**, 19–37.
Touré, A., Temgoua, E., Guenat, C. & Elberling, B. (2013) Land use and soil texture effects on organic carbon change in dryland soils, Senegal. *Open Journal of Soil Science*, **3**, 253–262.
Walker, S.M. & Desanker, P.V. (2004) The impact of land use on soil carbon in miombo woodlands of Malawi. *Forest Ecology and Management*, **203**, 345–360.
Wallenfang, J., Finckh, M., Oldeland, J. & Revermann, R. (2015) Impact of shifting cultivation on dense tropical woodlands in southeast Angola. *Tropical Conservation Science*, **8**, 863–892.
Wulder, M.A., Masekd, J.G., Cohen, W.B., Loveland, T.R. & Woodcock, C.E. (2012) Opening the archive: Hot free data has enabled the science and monitoring promise of Landsat. *Remote Sensing of Environment*, **121**, 2–10.
Yang, J. & Prince, S.D. (2000) Remote sensing of savanna vegetation changes in Eastern Zambia 1972–1989. *International Journal of Remote Sensing*, **21**, 301–322.

References [CrossRef]

Blake, G.R. & Hartge, K.H. (1986) Bulk density. *Methods of soil analysis, part 1: Physical and mineralogical methods* (ed. by A. Klute), pp. 363–375. Soil Science Society of America, Madison, WI.

Buresh, R.J., Smithson, P.C. & Hellums, D.T. (1997) Building soil phosphorus capital in Africa. *Replenishing soil fertility in Africa* (ed. by R.J. Buresh, P.A. Sanchez, & F. Calhoun), pp. 111–149. Soil Science Society of America and American Society of Agronomy, Madison, WI.

Chomba, B.M., Tembo, O., Mutandi, K., Mtongo, C.S. & Makano, A. (2012) *Drivers of deforestation, identification of threatened forests and forest co-benefits other than carbon from REDD+ implementation in Zambia.* Ministry of Lands, Natural Resources and Environmental Protection, Lusaka, Zambia.

Cornelissen, G., Martinsen, V., Shitumbanuma, V., Alling, V., Breedveld, G., Rutherford, D., Sparrevik, M., Hale, S., Obia, A. & Mulder, J. (2013) Biochar effect on maize yield and soil characteristics in five conservation farming sites in Zambia. *Agronomy*, **3**, 256–274. CrossRef

DeFries, R.S., Foley, J.A. & Asner, G.P. (2004) Land-use choices: Balancing human needs and ecosystem function. *Frontiers in Ecology and the Environment*, **2**, 249–257. CrossRef

Demessie, A., Singh, B.R. & Lal, R. (2013) Soil carbon and nitrogen stocks under chronosequence of farm and traditional agroforestry land uses in Gambo District, Southern Ethiopia. *Nutrient Cycling in Agroecosystems*, **95**, 365–375. CrossRef

Dijkshoorn, J.A. (2003) *SOTER database for Southern Africa (SOTERSAF).* ISRIC-World Soil Information, Wageningen, the Netherlands.

Eckmeier, E., Gerlach, R., Skjemstad, J.O., Ehrmann, O. & Schmidt, M.W.I. (2007) Minor changes in soil organic carbon and charcoal concentrations detected in a temperate deciduous forest a year after an experimental slash-and-burn. *Biogeosciences*, **4**, 377–383. CrossRef

Ellert, B.H. & Bettany, J.R. (1995) Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Canadian Journal of Soil Science*, **75**, 529–538. CrossRef

Frantz, D., Röder, A., Stellmes, M. & Hill, J. (2016) An operational radiometric Landsat preprocessing framework for large-area time series applications. *IEEE Transactions on Geoscience and Remote Sensing*, **54**, 3928–3943. CrossRef

Fynn, R.W.S., Haynes, R.J. & O'Connor, T.G. (2003) Burning causes long-term changes in soil organic matter content of a South African grassland. *Soil Biology and Biochemistry*, **35**, 677–687. CrossRef

Giardina, C., Sanford, R., Døckersmith, I. & Jaramillo, V. (2000a) The effects of slash burning on ecosystem nutrients during the land preparation phase of shifting cultivation. *Plant and Soil*, **220**, 247–260. CrossRef

Giardina, C.P., Sanford Jr., R.L. & Døckersmith, I.C. (2000b) Changes in soil phosphorus and nitrogen during slash-and-burn clearing of a dry tropical forest. *Soil Science Society of America Journal*, **64**, 399–405. CrossRef

Giller, K.E., Cadisch, G., Ehaliotis, C., Adams, E., Sakala, W.D. & Mafongoya, P.L. (1997) Building soil nitrogen capital in Africa. *Replenishing soil fertility in Africa* (ed. by R.J. Buresh, P.A. Sanchez, & F. Calhoun), pp. 151–192. Soil Science Society of America and American Society of Agronomy.

Hansen, M.C., Potapov, P. V., Moore, R. et al. (2013) High-resolution global maps of 21st-century forest cover change. *Science*, **342**, 850–854. CrossRef

Helmke, P.A. & Sparks, D.L. (1996) Lithium, sodium, potassium, rubidium, and cesium. *Methods of soil analysis, part 3: Chemical methods* (ed. by D.L. Spartks), pp. 551–574. Soil Science Society of America, Inc., Madison, WI.

Hird, J.N., Castilla, G. McDermid G.J.B., Bueno, I.T. (2016) A simple transformation for visualizing non-seasonal landscape change from dense time series of satellite data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **9**, 3372-3383. CrossRef

IUSS Working Group WRB (2014) *World reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps.* World Soil Resources Reports No. 106. FAO, Rome.

Janssen, B.H., Guiking, F.C.T., Van der Eijk, D., Smaling, E.M.A., Wolf, J. & Van Reuler, H. (1990) A system for quantative evaluation of the fertility of tropical soils (QUEFTS). *Geoderma*, **46**, 299–318. CrossRef

Jayne, T.S., Chamberlin, J. & Headey, D.D. (2014) Land pressures, the evolution of farming systems, and development strategies in Africa: A synthesis. *Food Policy*, **48**, 1–17. CrossRef

Jones, A., Breuning-Madsen, H., Brossard, M. et al. (2013) *Soil atlas of Africa*. European Commission, Publications Office of the European Union, Luxembourg.

Juo, A.S.R. & Manu, A. (1996) Chemical dynamics in slash-and-burn agriculture. *Agriculture, Ecosystems and Environment*, **58**, 49–60. CrossRef

Kauth, R.J. & Thomas, G. (1976) The tasselled cap--A graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. *LARS Symposia*, p. 159.

Kim, D.G., Thomas, A.D., Pelster, D., Rosenstock, T.S. & Sanz-Cobena, A. (2016) Greenhouse gas emissions from natural ecosystems and agricultural lands in sub-Saharan Africa: Synthesis of available data and suggestions for further research. *Biogeosciences*, **13**, 4789–4809. CrossRef

Kleinman, P.J.A., Pimentel, D. & Bryant, R.B. (1995) The ecological sustainability of slash-and-burn agriculture. *Agriculture, Ecosystems & Environment*, **52**, 235–249. CrossRef

Kuo, S. (1996) Phosphorous. *Methods of soil analysis, part 3* (ed. by D.L. Sparks), pp. 869–919. SSSA Book Series 5. Soil Science Society of America, Inc., Madison, WI.

Lenth, R.V. (2016) Least-squares means: The R package lsmeans. *Journal of Statistical Software*, **69**, 1–33. CrossRef

Luther-Mosebach, J. (2017) *Soil carbon stocks and dynamics in soils of the Okavango Catchment*, vol. 89. Hamburger Bodenkundlichen Arbeiten, Hamburg, Germany.

Mendelsohn, J., Jarvis, A., Roberts, C. & Robertson, T. (2002) *Atlas of Namibia: A portrait of the land and its people*. David Philip Publishers, Cape Town, South Africa.

Olofsson, P., Foody, G.M., Herold, M., Stehman, S.V., Woodcock, C.E. & Wulder, M.A. (2014) Good practices for estimating area and assessing accuracy of land change. *Remote Sensing of Environment*, **148**, 42–57. CrossRef

Petit, C., Scudder, T. & Lambin, E. (2001) Quantifying processes of land-cover change by remote sensing: Resettlement and rapid land-cover changes in south-eastern Zambia. *International Journal of Remote Sensing*, **22**, 3435–3456. CrossRef

Pinheiro, J., Bates, D., DebRoy, S., Sarker, D. & R Core Team (2012) *nlme: Linear and nonlinear mixed effects models.* R package version 3.1-131. https://cran.r-project.org/package=nlme

Pröpper, M., Gröngröft, A., Finckh, M., Stirn, S., Cauwer, V. De, Lages, F., Masamba, W., Murray-Hudson, M., Schmidt, L., Strohbach, B. & Jürgens, N. (2015) *The future Okavango – Findings, scenarios and recommendations for action*. Hamburg, Germany.

R Core Team (2017) *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/

Ribeiro Filho, A.A., Adams, C., Manfredini, S., Aguilar, R. & Neves, W.A. (2015) Dynamics of soil chemical properties in shifting cultivation systems in the tropics: A meta-analysis. *Soil Use and Management*, **31**, 474–482. CrossRef

Richards, J.A. (2013) *Remote sensing digital image analysis*. Springer, Berlin. CrossRef

Röder, A., Pröpper, M., Stellmes, M., Schneibel, A. & Hill, J. (2015) Assessing urban growth and rural land use

transformations in a cross-border situation in Northern Namibia and Southern Angola. *Land Use Policy*, **42**, 340–354. CrossRef
Röder, A., Stellmes, M., Frantz, D. & Hill, J. (2018) Operational generation of baseline products for environmental assessment and monitoring based on optical remote sensing data. *This volume*. CrossRef
Sattari, S.Z., van Ittersum, M.K., Bouwman, A.F., Smit, A.L. & Janssen, B.H. (2014) Crop yield response to soil fertility and N, P, K inputs in different environments: Testing and improving the QUEFTS model. *Field Crops Research*, **157**, 35–46. CrossRef
Schneibel, A., Röder, A., Stellmes, M. & Frantz, D. (2018) Long-term land use change analysis in south-central Angola. Assessing the trade-off between major ecosystem services with remote sensing data. *This volume*.
Stephenne, N. & Lambin, E. (2001) A dynamic simulation model of land-use changes in Sudano-Sahelian countries of Africa (SALU). *Agriculture, Ecosystems & Environment*, **85**, 145–161. CrossRef
Tittonell, P., Vanlauwe, B., Corbeels, M. & Giller, K.E. (2008) Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. *Plant and Soil*, **313**, 19–37. CrossRef
Touré, A., Temgoua, E., Guenat, C. & Elberling, B. (2013) Land use and soil texture effects on organic carbon change in dryland soils, Senegal. *Open Journal of Soil Science*, **3**, 253–262. CrossRef
Walker, S.M. & Desanker, P.V. (2004) The impact of land use on soil carbon in miombo woodlands of Malawi. *Forest Ecology and Management*, **203**, 345–360. CrossRef
Wallenfang, J., Finckh, M., Oldeland, J. & Revermann, R. (2015) Impact of shifting cultivation on dense tropical woodlands in southeast Angola. *Tropical Conservation Science*, **8**, 863–892. CrossRef
Wulder, M.A., Masekd, J.G., Cohen, W.B., Loveland, T.R. & Woodcock, C.E. (2012) Opening the archive: Hot free data has enabled the science and monitoring promise of Landsat. *Remote Sensing of Environment*, **121**, 2–10. CrossRef
Yang, J. & Prince, S.D. (2000) Remote sensing of savanna vegetation changes in Eastern Zambia 1972–1989. *International Journal of Remote Sensing*, **21**, 301–322. CrossRef

Farmer-wildlife conflicts in rural areas of eastern Zambia

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Abstract: Agricultural production of smallholder farmers can be significantly impacted by wildlife activity. In this study, we describe the forms of crop damages in the Lumimba Game Management Area in Lundazi District, Eastern Province of Zambia. Semi-structured questionnaires were administered to 131 randomly selected respondents. Crop damages are most frequent close to protected areas and decrease with increasing distances from these areas. As people invade habitats originally reserved for wildlife in order to cultivate food crops to support the growing human population, farmer-wildlife conflicts are likely to occur. Apart from conflicts over crops, local farmers illegally kill wild animals for bushmeat for economic reasons. A combination of countermeasures against crop damages may be effective at the farm level.

Resumo: A produção agrícola dos pequenos agricultores pode ser bastante afectada pela vida selvagem. Neste estudo, descrevemos os vários danos às culturas na Área de Gestão Cinegética de Lumimba, no distrito de Lundazi, Província Oriental da Zâmbia. Questionários semi-estruturados foram realizados a 131 pessoas seleccionadas aleatoriamente. Os danos às culturas são mais frequentes perto das áreas protegidas e diminuem com o aumento da distância a estas áreas. Uma vez que as pessoas invadem habitats originalmente reservados à vida selvagem, a fim de cultivarem culturas que possam suportar a população humana em crescimento, é provável que ocorram conflictos entre os agricultores e a fauna selvagem. Para além dos conflictos devido às culturas, os agricultores locais matam ilegalmente animais selvagens para consumo por questões económicas. Uma combinação de contramedidas contra os danos agrícolas poderá ser efectiva ao nível da quinta.

Introduction

Conflicting land uses are often due to competing claims by users such as farmers and natural resource stakeholders such as wildlife agencies and conservation organisations (Giller et al., 2008). Rising human populations in wildlife-agrarian landscapes increase the chances of inconsistent access to land, food availability and quality, and economic stability (FAO, 2008). If human activities are not regulated, they are likely to lead to overexploitation of wildlife resources for food and commercial purposes.

The framing and implementation of any potential solutions to this issue must be transformative, thus changing the mindset and self-reflections of the local communities. Locals' wish to improve their economic situation results in overexploitation of natural resources to meet the needs of the growing human population, even more so given the threats of crop damages and climate change, which can cause crop failure due to extreme weather conditions like floods and droughts (Takasaki et al., 2004). In resolving the issue of crop damages, there is a need for broad-based participation by local communities and other stakeholders in planning and decision making (Shackleton & Campbell, 2000). Therefore, local stakeholder participation such as practicing effective land management for sustainable agriculture should be viewed in the broader context of adaptive governance (Folke et al., 2005). Governance can be defined as a process and structural framework for exercising rights and responsibilities by the stakeholders over public concerns (Graham et al., 2003). The objective of this study was to investigate the nature of farmer-wildlife conflicts and how such conflicts influence food security in wildlife-agrarian landscapes as found in the Luangwa Valley.

Methods

The underlying study was conducted in the Lumimba Game Management Area (GMA), which occupies 4 500 km^2 in the Luangwa Valley, eastern Zambia (Fig. 1). Lumimba GMA is surrounded by four national parks (NPs): North Luangwa, South Luangwa, Luambe, and Lukusuzi. GMA policy permits multiple land uses such as agriculture, infrastructure, and commercial trophy hunting in designated land-use zones within the area. As of 2012, the Lumimba GMA had 8 679 inhabitants com-

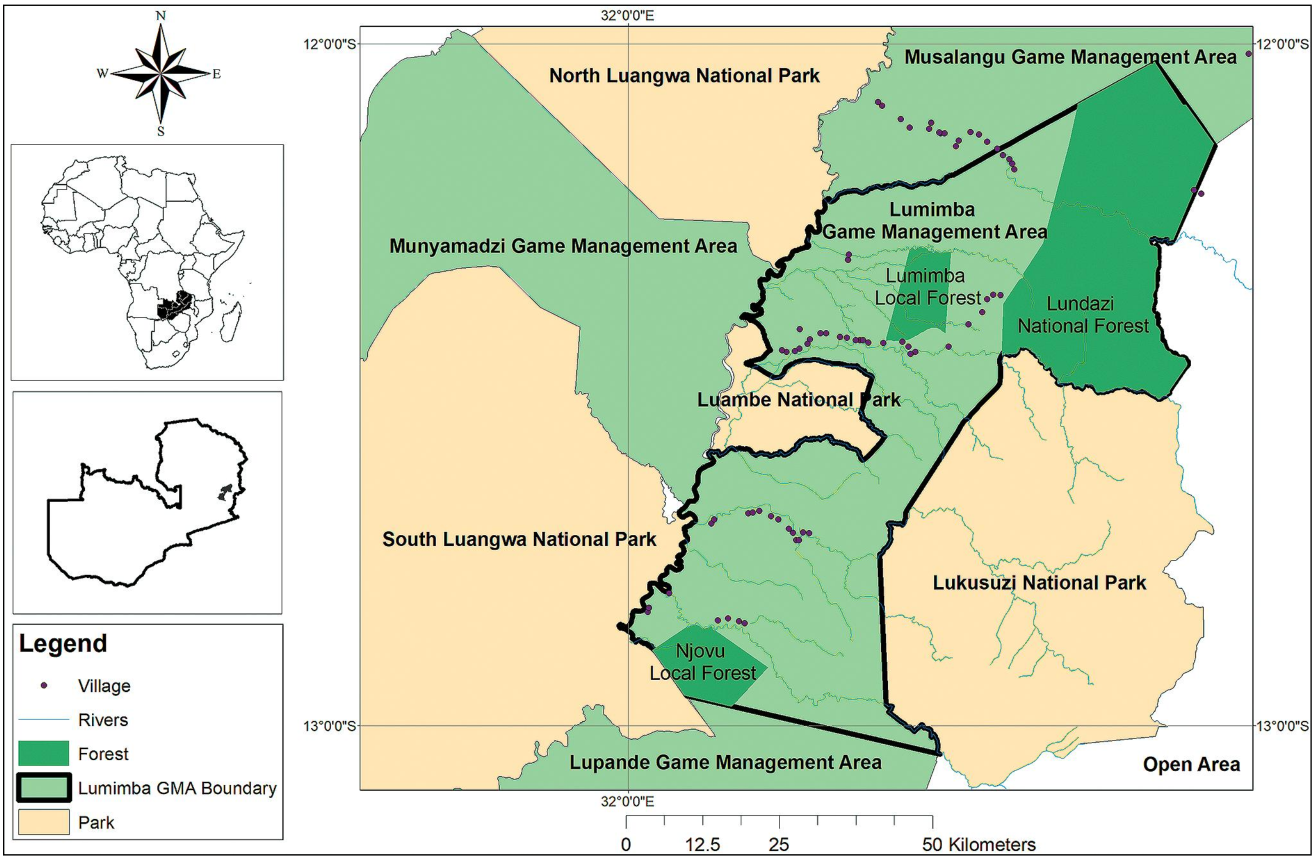

Figure 1: Location of Lumimba Game Management Area, eastern Zambia.

prising a total of 1 654 households and an annual average rate of population increase of 3% (Central Statistical Office, 2012). In the Luangwa Valley, local farmers face pervasive crop depletion from wildlife (Nyirenda et al., 2011).

Perception data was gathered in 2014, a year with average environmental conditions, using semi-structured questionnaires (Tab. 1) administered to 131 randomly selected participants drawn from different households in 44 out of 53 villages within the Lumimba GMA. Selection of participants was based on the village registers. Several households of closely related people, usually sharing family or clan ties, constituted these villages. Male- and female-headed households were interviewed in exclusive interviews (Fig. 2). Each interview lasted about 50 minutes. Open questions (Tab. 1) were administered to respondents to gather in-depth data on crop damages (Patton, 2002). We sought prior, free, and informed consent from the participants at the beginning of the interviews (Bradburn et al., 2004). We also assured them of the confidentiality of their responses.

Table 1: Excerpt of semi-structured questionnaires conducted in Lumimba Game Management Areas, Luangwa Valley, Zambia in 2014

a) What is the nature of the farmer-wildlife conflicts in Lumimba GMA?
b) Which of the existing land use types conflict with each other in Lumimba GMA?
c) Using your memory, what do you perceive as the status of crop raiding, whether decreasing, increasing or stable, in the last five years in your area?
d) In contrast to the existing land use types, what do you perceive as your main source of livelihood?
e) What are your coping and alleviating strategies against crop damages?
f) What are the drivers of farmer-wildlife conflicts in Lumimba GMA?
g) Which animals cause the most crop damages?
h) What methods do you employ or practice to tackle crop damages?
i) How effective are they in stopping or reducing crop damages?
j) What remedial actions do you propose against crop damages?
k) What external and internal solutions would you propose to strengthen local collective actions against crop damages?

Given the qualitative data gathered, a thematic content analysis technique was adopted to obtain interpretive sources of local social constructs (Guest, 2012).

Results

The interviewees' responses explained local land-use conflicts between agriculture and wildlife. Most of the respondents (95%; n=117) reported habitat loss due to inappropriate agricultural practices, as well as depletion of wildlife from bushmeat harvesting for subsistence and commercial purposes. Retaliatory hunting of wildlife was also reported to occur as a byproduct of crop damages. Further, respondents perceived crop damage levels as reflected in Figure 3. All the participants indicated that farming of crops such as maize (*Zea mays*) comprised the

Figure 2: Interview session with a household head.

mainstay livelihood in the area. Other crops grown included rice (*Oryza sativa*), cotton (*Gossypium hirsutum*), cassava (*Manihot esculenta*), pumpkins (*Curcubita maxima*), groundnuts (*Arachis hypogaea*), sweet potatoes (*Ipomoea batatas*), cabbages (*Brassica oleracea*), rape (*Brassica napus*), onions (*Allium cepa*), and tomatoes (*Lycopersicon esculentum*). The crops most heavily impacted by wildlife were ranked in order as maize, rice, cotton, cassava, and pumpkin. Most respondents (52%; n=64) indicated that African elephants (*Loxodonta africana*) caused the most crop damages, primarily adjacent to the Luambe, South Luangwa, and North Luangwa NPs. Lukusuzi NP was considered largely depleted of wildlife. Other wildlife species causing crop damages in Lumimba GMA were ranked as rats (*Rattus rattus*), hippopotamus (*Hippopotamus amphibious*), bushpig (*Potamochoerus larvatus*), warthog (*Phacochoerus africanus*), greater kudu (*Tragelaphus strepsiceros*), yellow baboon (*Papio cynocephalus*), eland (*Taurotragus oryx*), and porcupine (*Hystrix africaeustralis*). The annual median time for the local populace to run out of food as a result of crop damages and other reasons such as crop failure was three months (range: 1 month–4 months), depending on proximity to the parks (Fig. 4), especially approaching and during the rainy season. More crops were lost to raiding of food stores by wildlife than to raiding in the fields (Fig. 5). Food stores, which were temporary structures made of mud, wood, and thatch, concentrated the crops and made these stores easily accessible to elephants and rats. The local communities coped with crop losses and alleviated food shortages by poaching to obtain bushmeat for both subsistence and commercial purposes. They also acquired relief food from the government and the World Food Programme based on issues of widespread food shortages in the area. Further, they exchanged valuable items such as on-farm labour for food, and received funds remittances from urban-dwelling relatives and friends.

Poverty (i.e., inability to secure basic life requirements such as daily food) among the growing human population in the area was ranked first by many of the respondents (91%; n=112) as the key driver of crop damages after elephants. Habitat loss was ranked second. Weak local institutional governance (for instance, feeble decision making, irregular conduct of public meetings to address crop raiding, inability to protect resources from abuse, and inability to implement punitive measures against rule infractions) was ranked third. The farmers in the Lumimba GMA employed traditional countermeasures against wildlife damages, such as crop guarding including the use of watchtowers, fires, cans, shouting, drumming and clapping, chilli pepper balls/bombs, and fences. Because

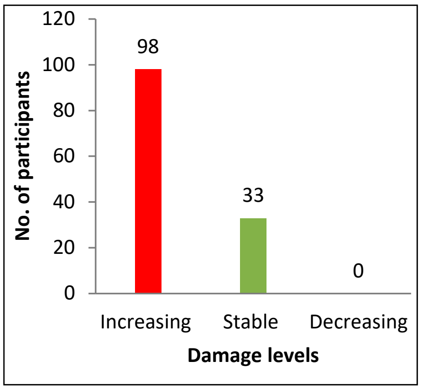

Figure 3: Interviewees' perceptions of crop damages in Lumimba GMA, 2014.

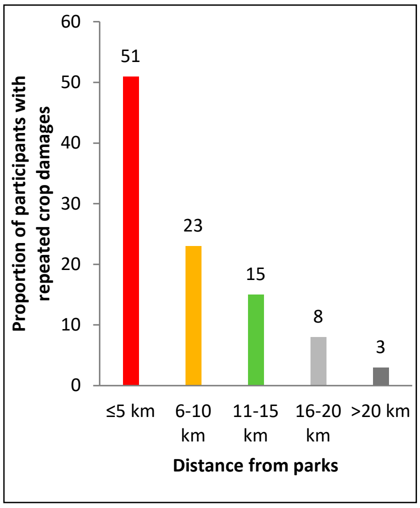

Figure 4: Varying crop damages with distances from the parks, affecting food availability within Lumimba GMA communities, 2014.

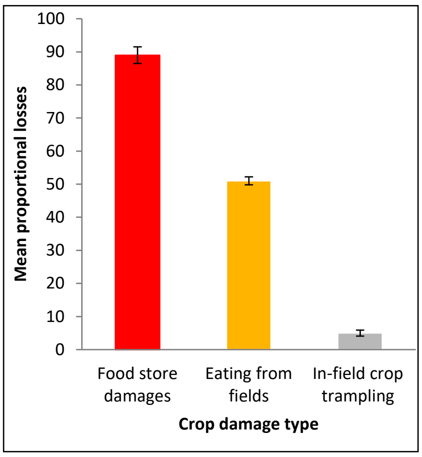

Figure 5: Perceived proportional crop losses to wildlife across crop damage types in Lumimba GMA, 2014.

these countermeasures were considered ineffective due to elephant habituation (96%, n=126), participants preferred to employ long-term and large-scale private and donor investments, for instance, electric fencing installed through public-private-community partnerships (72%, n=88) and joint ventures (25%, n=31). Some funds have been generated from commercial wildlife hunting that takes place annually in the area. While the government retains some portion of the funds generated by commercial wildlife hunting, the local community is also given part of these funds for community priority projects such as provision of water for domestic uses, construction of health posts and community schools, and resource protection. The interviewees perceived that enhanced capital funding would be critical input into remedial actions regarding crop damages. A preponderance of respondents (72%, n=88) indicated they received waning cooperative support from local organizations such as the Community Resources Board (CRB) at the time of the study. The CRB is a local policy body, constituted by democratically elected members of the local community with a fixed tenure of office of three years within the Community Based Natural Resource Management (CBNRM) approach. Its main function is to spearhead rights-based participation of the local community in resource protection and rural development. The desired actors for the future implementation of interventions to address crop damages included government, community-based organizations, local farmers, commercial trophy and indigenous hunters, and non-governmental organizations.

Discussion

In the Lumimba GMA, farmers practice traditional farming using basic implements and inputs, with modest crop management. They seek new, seemingly fertile lands through agricultural expansions and clearing of savannah woodland, where they also establish new human settlements in the form of villages. Their crop fields are also placed in areas that were originally wildlife habitats. Inevitably, such areas become conflict zones in which crops suffer incursions by wildlife. Farmers' failure to effectively protect crop fields and storage facilities has contributed to crop losses. In addition, farmers' failure to comply with zoning restrictions such as prohibition of crop cultivation in wildlife protection zones stipulated in the management plans for the area (developed with farmers' input in multidisciplinary and participatory processes) renders the area vulnerable to continued human encroachment into wildlife habitats. The management plans are a legal provision in Zambia's wildlife legislation to ensure effective management of natural resources in the protected areas while providing for rural development and fostering local livelihoods. In the GMA, the primary land use is wildlife management, although regulated additional land uses such as agriculture and human settlement are also permitted. At the time the GMA was established in 1972, only a few villages existed in the area; these have since grown in number due to splitting of households within the area and the influx of settlers from outside the GMA. Implementation of land-use plans can be a helpful management tool in reducing conflicting multiple land uses (FAO, 2006) and protecting sensitive wildlife habitats (Green & Higginbottom, 2000), as such plans are intended to guide where, when, and how specific anthropogenic activities should be conducted across a landscape. A land-use plan would typically include zones dedicated to specific purposes such as agriculture and wildlife habitat management. The establishment of zones is intended to be consensual and transformative in nature, whereby vulnerable or degrading areas are protected and benefit from positive change in human behaviour and attitude towards the environment. Further, local communities can play self-empowering roles to relieve potential pressures from overuse of natural resources through employing alternative livelihoods (Child, 2009; Fernandez et al., 2009). Bushmeat overexploitation, especially in times of famine, has the potential to reduce wildlife populations available for trophy hunting and photographic purposes (Rosenblatt et al., 2014). However, bushmeat hunting for subsistence and commercial purposes is a lucrative social safety net for some members of local communities (Lindsey et al., 2013). The wildlife populations may also decline from retaliatory killings by farmers over their crop losses (Hoare, 2012). Such occurrences may potentially render GMAs less productive (Lindsey et al., 2014), alongside the impact of animal die-offs as an effect of droughts. The funds generated from commercial wildlife hunting, based on limited animal quotas, are considered too small to offset the crop losses experienced in the area. Zambia does not have a direct compensation policy in the form of individual dividends paid to farmers for the crop losses caused by wildlife.

Weak institutional governance has long been recognised as a contributing factor to a number of environmental challenges, including human encroachment into wildlife habitats and illegal wildlife killings among the local communities (Barrett et al., 2001). There is a need for local communities to be much more involved in environmental management. They must seek and implement solutions to crop damages through such interventions as decision making, regularly conducting public meetings to address crop raiding, resource protection, and implementing countermeasures against crop damages. The Department of National Parks and Wildlife, which is the key player in wildlife management in the region, faces a number of challenges, such as inadequate funding and staffing, which hinder it from productively contributing to the resolution of farmer-wildlife conflicts. Therefore, the area may benefit from effective partnerships that would build capacity among the key players to address crop damages.

Though often deemed ineffective, farmers commonly apply traditional countermeasures as mitigation methods against crop incursions. Traditional methods are inexpensive to implement and knowledge about these techniques is passed across human generations. Use of traditional countermeasures potentially reduces transaction costs over time through collective action, such as in the case of mobilisation of crop guards for the benefit of contemporary users.

Collective action entails horizontal collaboration (community members working with each other) and vertical collaboration (community members networking with outsiders) in planning and implementing farmer-wildlife conflict countermeasures. Vertical collaboration may further include strengthening the practice of such local initiatives as the Community Markets for Conservation (COMACO) model, which promotes the nexus of conservation and agriculture (Lewis et al., 2011). Under the COMACO model, farmers are grouped into farming cooperatives. Within these cooperatives, they receive training on farming best practices such as conservation farming and crop protection. Farmers are also linked to appropriate markets for their produce, where they earn premiums upon satisfactorily participating in the conservation of natural resources through various compliances.

Further, local capacity can be built through partnerships within the relational social capital realm (i.e., trust, commitment, cooperation, and connectedness) among local farmers and other stakeholders. The partnerships may take various forms, including public-private partnerships (PPP) and joint ventures (JV), in addition to supportive and enabling policy changes. For instance, increased benefits from neighbouring parks can include contractual arrangements for ecotourism concessions by wildlife agencies partnering with local communities (Nelson, 2004). Such interventions offer competitive advantages for involved parties such as farmers, tour operators, and the Department of National Parks and Wildlife and may include benefits such as growing wildlife populations. As public entities, local communities, including farmers, have the added value of possessing indigenous knowledge regarding resource management and may offer readily available labour, to which requisite technical skills can be imparted by other partners such as tour operators and the Department of National Parks and Wildlife. The private sector may play an important role in attracting additional investments and tourists for increased revenue generation, and may even provide supportive models for wildlife management and agriculture. Farmers are likely to support conservation efforts and produce positive ecological, socioeconomic, and governance impacts if they perceive increased benefits from such activities (Jones & Weaver, 2009).

Conclusion

Our study reveals that crop damages inflicted by wildlife deprive farmers of their food security in the Lumimba GMA. The currently employed countermeasures remain ineffective. Improved mitigation methods and GMA management models are urgently needed in the region. Experimentation with novel methods in order to provide farmers with more options will be critical due to habituation by some wildlife species such as elephants. Adoption of the appropriate methods and models by the farmers will also be paramount. Though wildlife- and agriculture-based land uses seem antithetical to one another in much of Africa (Lamarque et al., 2009), parks—people relationships can foster wildlife conservation and agriculture beyond park boundaries through provision of intemperance benefits (Anthony, 2007). Harnessing benefits that would encourage local support relies on increased levels of relational social capital generated by stronger local institutions than those that exist at present (Barrett et al., 2005). Therefore, there is a notable need for training and re-training the local communities in new livelihood alternatives. Currently, agriculture still remains farmers' main source of food and income, and is the livelihood activity of which farmers have the most adaptive knowledge. In tackling the challenges posed by crop damages, there is also a need to emphasise relational social capital in addition to other forms of capital such as financial capital to keep wildlife away from the crop fields and food stores. Proper zoning of wildlife and agriculture areas and use of cluster wire fencing may be some of the more effective measures available to farmers at the farm level.

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References

Anthony, B. (2007) The dual nature of parks: Attitudes of neighbouring communities towards Kruger National Park, South Africa. *Environmental Conservation*, **34**, 236–245.

Barrett, C.B., Brandon, K., Gibson, C. & Gjertsen, V. (2001) Conserving tropical biodiversity amid weak institutions. *BioScience*, **51**, 497–502.

Barrett, C.B., Lee, D.R. & McPeak, J.G. (2005) Institutional arrangements for rural poverty reduction and resource conservation. *World Development*, **33**, 193–197.

Bradburn, N., Sudman, S. & Wansink B. (2004) *Asking questions: The definitive guide to questionnaire design–for market research, political polls, and social and health questionnaires*, John Wiley & Sons, Jossey-Bass, Hoboken, NJ.

Central Statistical Office. (2012) Zambia 2010 census of population and housing: Population summary report. Central Statistical Office, Lusaka.

Child, B. (2009) Recent innovations in conservation. *Evolution and innovation in wildlife conservation: Parks and game ranches to transfrontier conservation areas* (ed. by H. Suich, B. Child & A. Spenceley), pp. 277–287. Earthscan, London.

FAO. (2006) Land tenure alternative conflict management. FAO land tenure manuals 2. FAO, Rome.

FAO. (2008) Challenges for sustainable land management for food security in Africa. 25th Regional Conference for Africa, Information paper 5, p. 15, Nairobi, Kenya.

Fernandez, A., Richardson, R.B., Tschirley, D. & Tembo, G. (2009) Wildlife conservation in Zambia: Impact on rural household welfare. Working Paper no. 41. Food Security Policy Research Institute, Lusaka, Zambia.

Folke, C., Hahn, T., Olsson, P. & Norberg, J. (2005) Adaptive governance of social-ecological system. *Annual Review of Environmental Resources*, **30**, 441–473.

Giller, K.E., Leeuwis, C., Andersson, J.A., et al. (2008) Competing claims on natural resources: What role for science? *Ecology and Society*, **13**, 34.

Green, R. & Higginbottom, K. (2000) The effects of non-consumptive wildlife tourism on free-ranging consumptive wildlife tourism: A review. *Conservation Biology*, **6**, 183–197.

Guest, G. (2012) *Applied thematic analysis*. Sage Publications, Thousand Oaks, CA.

Food security

Graham, J., Amos, B. & Plumptre, T. (2003) *Governance principles for protected areas in the 21st century*. Institute on Governance, Ottawa.

Hoare, R. (2012) Lessons from 15 years of human-elephant conflict mitigation: Management considerations involving biological, physical, and governance issues in Africa. *Pachyderm*, **51**, 60−74.

Jones, B. & Weaver, C. (2009) CBNRM in Namibia: Growth, trends, lessons, and constraints. *Evolution and innovation in wildlife conservation: Parks and game ranches to transfrontier conservation areas* (ed. by H. Suich, B. Child & A. Spenceley), pp. 223−242. Earthscan, London.

Lamarque, F., Anderson, J., Fergusson, R., Lagrange, M., Osei-Owusu Y. & Bakker, L. (2009) *Human- wildlife conflict in Africa: Causes, consequences, and management strategies*. FAO, Rome.

Lewis, D., Bell, S.D., Fay, J., et al. (2011) Community markets for conservation (COMACO) links biodiversity conservation with sustainable improvements in livelihoods and food production. *Proceedings of the National Academy of Sciences*, **108**, 13957−13962.

Lindsey, P.A., Nyirenda, V.R., Barnes, J.I., Becker, M.S., McRobb, R., Tambling, C.J., Andrew Taylor, W., Watson, F.G. & t'Sas-Rolfes, M. (2014) Underperformance of African protected area networks and the case for new conservation models: Insights from Zambia. *PLoS ONE*, **9**, e94109.

Lindsey, P., Balme, G., Becker, M., et al. (2013) The bushmeat trade in African savannas: Impacts, drivers, and possible solutions. *Biological Conservation*, **160**, 80–96.

Nelson, F. (2004) *The evolution and impacts of community-based photo-tourism in northern Tanzania*. International Institute for Environment and Development, London.

Nyirenda, V.R., Chansa, W.C., Myburgh, W.J. & Reilly, B.K. (2011) Wildlife crop depredation in the Luangwa Valley, eastern Zambia. *Journal of Ecology and the Natural Environment*, **3**, 481–491.

Patton, M.Q. (2002) *Qualitative research and evaluation methods*, 3rd edn. Sage Publications, London.

Rosenblatt, E., Becker, M.S., Creel, S., Droge, E. Mweetwa, T., Schuette, P.A., Watson, F., Merkle, J. & Mwape, H. (2014) Detecting declines of apex carnivores and evaluating their causes: An example with Zambian lions. *Biological Conservation*, **180**, 176–186.

Shackleton, S. & Campbell, B. (eds.) (2000) Empowering communities to manage natural resources: Case studies from southern Africa. Southern African Development Community (SADC) Wildlife Sector–Natural Resources Management Programme, Lilongwe, Malawi.

Takasaki, Y., Barham, B.L. & Coomes, O.T. (2004) Risk coping strategies in tropical forests: Floods, illnesses, and resource extraction. *Environment and Development Economics*, **9**, 203−224.

References [CrossRef]

Anthony, B. (2007) The dual nature of parks: Attitudes of neighbouring communities towards Kruger National Park, South Africa. *Environmental Conservation*, **34**, 236−245. CrossRef

Barrett, C.B., Brandon, K., Gibson, C. & Gjertsen, V. (2001) Conserving tropical biodiversity amid weak institutions. *BioScience*, **51**, 497−502. CrossRef

Barrett, C.B., Lee, D.R. & McPeak, J.G. (2005) Institutional arrangements for rural poverty reduction and resource conservation. *World Development*, **33**, 193−197. CrossRef

Bradburn, N., Sudman, S. & Wansink B. (2004) *Asking questions: The definitive guide to questionnaire design–for market research, political polls, and social and health questionnaires*, John Wiley & Sons, Jossey-Bass, Hoboken, NJ.

Central Statistical Office. (2012) Zambia 2010 census of population and housing: Population summary report. Central Statistical Office, Lusaka.

Child, B. (2009) Recent innovations in conservation. *Evolution and innovation in wildlife conservation: Parks and game ranches to transfrontier conservation areas* (ed. by H. Suich, B. Child & A. Spenceley), pp. 277−287. Earthscan, London.

FAO. (2006) Land tenure alternative conflict management. FAO land tenure manuals 2. FAO, Rome.

FAO. (2008) Challenges for sustainable land management for food security in Africa. 25th Regional Conference for Africa, Information paper 5, p. 15, Nairobi, Kenya.

Fernandez, A., Richardson, R.B., Tschirley, D. & Tembo, G. (2009) Wildlife conservation in Zambia: Impact on rural household welfare. Working Paper no. 41. Food Security Policy Research Institute, Lusaka, Zambia.

Folke, C., Hahn, T., Olsson, P. & Norberg, J. (2005) Adaptive governance of social-ecological system. *Annual Review of Environmental Resources*, **30**, 441−473. CrossRef

Giller, K.E., Leeuwis, C., Andersson, J.A., et al. (2008) Competing claims on natural resources: What role for science? *Ecology and Society*, **13**, 34. CrossRef

Green, R. & Higginbottom, K. (2000) The effects of non-consumptive wildlife tourism on free-ranging consumptive wildlife tourism: A review. *Conservation Biology*, **6**, 183−197. CrossRef

Guest, G. (2012) *Applied thematic analysis*. Sage Publications, Thousand Oaks, CA. CrossRef

Graham, J., Amos, B. & Plumptre, T. (2003) *Governance principles for protected areas in the 21st century*. Institute on Governance, Ottawa.

Hoare, R. (2012) Lessons from 15 years of human-elephant conflict mitigation: Management considerations involving biological, physical, and governance issues in Africa. *Pachyderm*, **51**, 60−74.

Jones, B. & Weaver, C. (2009) CBNRM in Namibia: Growth, trends, lessons, and constraints. *Evolution and innovation in wildlife conservation: Parks and game ranches to transfrontier conservation areas* (ed. by H. Suich, B. Child & A. Spenceley), pp. 223−242. Earthscan, London.

Lamarque, F., Anderson, J., Fergusson, R., Lagrange, M., Osei-Owusu Y. & Bakker, L. (2009) *Human- wildlife conflict in Africa: Causes, consequences, and management strategies*. FAO, Rome.

Lewis, D., Bell, S.D., Fay, J., et al. (2011) Community markets for conservation (COMACO) links biodiversity conservation with sustainable improvements in livelihoods and food production. *Proceedings of the National Academy of Sciences*, **108**, 13957−13962. CrossRef

Lindsey, P.A., Nyirenda, V.R., Barnes, J.I., Becker, M.S., McRobb, R., Tambling, C.J., Andrew Taylor, W., Watson, F.G. & t'Sas-Rolfes, M. (2014) Underperformance of African protected area networks and the case for new conservation models: Insights from Zambia. *PLoS ONE*, **9**, e94109. CrossRef

Lindsey, P., Balme, G., Becker, M., et al. (2013) The bushmeat trade in African savannas: Impacts, drivers, and possible solutions. *Biological Conservation*, **160**, 80–96. CrossRef

Nelson, F. (2004) *The evolution and impacts of community-based photo-tourism in northern Tanzania*. International Institute for Environment and Development, London.

Nyirenda, V.R., Chansa, W.C., Myburgh, W.J. & Reilly, B.K. (2011) Wildlife crop depredation in the Luangwa Valley, eastern Zambia. *Journal of Ecology and the Natural Environment*, **3**, 481–491.

Patton, M.Q. (2002) *Qualitative research and evaluation methods*, 3rd edn. Sage Publications, London.

Rosenblatt, E., Becker, M.S., Creel, S., Droge, E. Mweetwa, T., Schuette, P.A., Watson, F., Merkle, J. & Mwape, H. (2014) Detecting declines of apex carnivores and evaluating their causes: An example with Zambian lions. *Biological Conservation*, **180**, 176–186. CrossRef

Shackleton, S. & Campbell, B. (eds.) (2000) Empowering communities to manage natural resources: Case studies from southern Africa. Southern African Development Community (SADC) Wildlife Sector–Natural Resources Management Programme, Lilongwe, Malawi.

Takasaki, Y., Barham, B.L. & Coomes, O.T. (2004) Risk coping strategies in tropical forests: Floods, illnesses, and resource extraction. *Environment and Development Economics*, **9**, 203−224. CrossRef

Food security

Diversity of wild herbaceous legumes in Southern Africa, their associated root nodule bacteria, and insect pests

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Abstract: Climate change models predict that most parts of southern Africa including Botswana and Namibia will experience severe water stress and temperature increases as a result of climate change. Wild drought-tolerant nitrogen-fixing plants with heat-tolerant bacterial symbionts might be a source for mitigation, nutrient-rich grazing grounds, and soil fertility. Herbaceous legumes may be developed into forage plants that are resilient to climate change effects. Therefore, the purpose of the study was to assess the diversity of wild herbaceous legumes in the north-western and eastern parts of Botswana, northern parts of Namibia, and Northern Cape of South Africa. They were assessed for nodulation and insect damage, root nodule bacteria were isolated, and some were identified and authenticated on their homologous hosts. In Namibia, rhizosphere bacteria were isolated and characterised. For the first time, it was shown that a wide range of wild legumes in the study area were nodulated. Common plant species included, amongst others, *Chamaecrista bieinsis* (Stey.) Lock, *Chamaecrista absus* (L.) Irwin and Barneby, *Zornia glochidata* DC, and several *Crotalaria* and *Indigofera* species. The jewel beetle *Sphenoptera* sp. damaged over 90% of the *Indigofera* sp. in Lecheng. The bacteria isolated were typical plant growth–promoting bacteria mostly belonging to the *Bacillus* and *Brevibacillus* genera, with fewer rhizobial species. Such bacteria may be valuable inoculants for pulses and cereals, respectively. Taken together, the results of this study highlight the potential for herbaceous legumes in mitigating climate change effects through the use of inoculants as biofertiliser and through use in intercropping that modulates pest infestation, leading to low usage of chemical pesticides.

Resumo: Os modelos de alterações climáticas prevêem que a maior parte do Sul de África, incluindo o Botswana e a Namíbia, irá sofrer stress hídrico e um aumento da temperatura severos. Plantas silvestres fixadoras de azoto e tolerantes à seca, com bactérias simbiontes tolerantes ao calor, poderão ser uma fonte de mitigação para campos de pastagem ricos em nutrientes e fertilidade do solo. Leguminosas herbáceas poderão ser desenvolvidas em plantas forrageiras que são resilientes aos efeitos das alterações climáticas. Assim, o propósito do estudo foi avaliar a diversidade de leguminosas herbáceas silvestres no Noroeste e Nordeste do Botswana, Norte da Namíbia e Cabo Norte da África do Sul. Foram avaliadas quanto à nodulação, danos por insectos e bactérias dos nódulos radiculares foram isoladas, algumas identificadas e autenticadas nos seus hospedeiros homólogos. Na Namíbia, bactérias da rizosfera foram isoladas e caracterizadas. Pela primeira vez, foi demonstrado que uma grande variedade de legumes silvestres estava nodulada na área de estudo. As espécies de plantas comuns incluiram, entre outras, *Chamaecrista bieinsis* (Stey.) Lock, *Chamaecrista absus* (L.) Irwin e Barneby, *Zornia glochidata* DC., bem como diversas espécies de *Crotalaria e Indigofera*. O besouro *Sphenoptera* sp. danificou mais de 90% de *Indigofera* sp. em Lecheng. As bactérias isoladas eram bactérias típicas promotoras de crescimento vegetal, maioritariamente pertencentes aos géneros *Bacillus* e *Brevibacillus*, com menos espécies de rizóbios. Tais bactérias podem ser inoculantes valiosos para legumes e cereais, respectivamente. No geral, os resultados deste estudo destacam o potencial das leguminosas herbáceas na mitigação dos efeitos das alterações climáticas através do uso de inoculantes como biofertilizantes e de culturas alternadas, as quais modulam a infestação por pragas, levando a um menor uso de pesticidas químicos.

Introduction

Nitrogen is unique among the other essential plant nutritional elements because N_2 from the atmosphere can be fixed via biological nitrogen fixation (BNF), carried out exclusively by prokaryotes that possess the enzyme nitrogenase. Nitrogen input by symbiotic plant-microbe interactions not only improves soil fertility (Grönemeyer et al., 2014) but also enhances the productivity of the ecosystem and provides protein-rich plant biomass for grazing. However, there is very little published knowledge on rhizobial symbionts of crops from Namibia, Angola, and Botswana (Pule-Meulenberg & Dakora, 2007). In addition to nodulated legumes and N_2-fixing legumes, in this study it is appreciated that there are many microorganisms that reside in the root nodules of legumes and generally in the rhizosphere of all plants. The role of such organisms is that of plant growth promotion through various mechanisms.

There are many wild legume species that are important to local communities. Examples include use as grazing resources for livestock (Nezomba et al., 2008; Madibela et al., 2018), building material, food, medicinal resources (Pule-Meulenberg & Dakora, 2007), and green manure (Nezomba et al., 2008) for rural and urban communities. Nevertheless, the economic importance of many plant species is still largely unknown. In natural ecosystems where wild legumes grow, in addition to cycling N, they provide food to insect herbivores. Naturally, plants interact with an array of arthropod species, microbes, and other plants both below and above ground. Although some of these interactions may be detrimental, such as instances where insects feed on translocated nutrients from the plant, there are cases where mutualism occurs. Detrimental effects of plant-insect interaction may be major constraints if wild legumes are to be utilized as sources of nutrients and livestock feed in future.

These wild legumes are well adapted to the harsh environmental conditions such as high temperature, low soil moisture, winter drought, high incidence of pests, soil acidity, and soil salinity that are prevalent in Botswana, Namibia, and other countries in southern Africa. This may also extend to their symbionts, as they have to survive in the soil under these conditions. For example, in Namibia, where high soil temperatures prevail, novel *Bradyrhizobium* isolates were found to be also well adapted, showing extraordinarily high temperature tolerance (Grönemeyer et al., 2014). Projections of consequences of climate change at the local scale indicated that the Kavango basin will become warmer (1.5–2.5°C) and receive less mean annual precipitation (50–100 mm) until 2045 (Pröpper et al., 2015). Hotter and drier climates, loss and degradation of soil, crop failure, and increase in population are the main issues that have to be dealt with.

In addition to harbouring N_2-fixing bacteria, both wild and domesticated legume species are known to harbour bacterial strains with plant growth–promoting traits, phosphate solubilisation, siderophore production, phytohormone production, or triggering of plant defence responses by various mechanisms (Grönemeyer et al., 2012; Burbano et al., 2015; Chimwamurombe et al., 2016).

Generally in Africa, farmers continue to obtain low yields because of the non-replacement of nutrients year after year, leading to declining soil fertility in smallholder farms under dryland conditions. Unfortunately, the majority of African small farmers are not able to afford the high mineral fertilizer prices (Yanggen et al., 1998). Low-cost and sustainable technical solutions compatible with the socioeconomic conditions of small farmers are needed to solve soil fertility and yield problems (Chianu et al., 2011). Also in the northern regions of Namibia and in the North-West District of Botswana, rainfed agriculture is practised by smallholder farms with very low crop yields and also poorly developed value chains and food processing. The resource-poor farmers do not use chemical fertilizers, manure, or other inputs but are prone to slash-and-burn agriculture. Previous soil analyses have shown that the key mineral nutrients N and P are very low in these sandy soils (Gröngröft et al., 2013), and dryland farming lowers carbon pools and nutrient levels (Wisch et al. 2008; Luther-Mosebach et al., 2015). Arbuscular mycorrhiza might be useful for P-acquisition, but inoculant production from the nonculturable fungi is challenging. The use of herbaceous legumes as green manure and as a source of elite biofertiliser strains for plant growth promotion can be regarded as sustainable agriculture. The use of inorganic fertilisers has been associated with greenhouse gas emission (Linquist et al., 2012) and pollution of underground water resources, particularly nitrate pollution (Gao et al., 2012). Polycultures using legumes are known to reduce pest population pressure on crops, thereby reducing the use of chemical pesticides (Amoako-Atta et al., 1983). Furthermore, over-reliance on pesticides increases environmental pollution, which contributes to environmental change. Hence, the use of herbaceous legumes and their associated microorganisms can be used as a strategy to improve soil fertility and reduce pests sustainably with minimal environmental pollution. Therefore, the purpose of the study was to assess the diversity of wild herbaceous legumes in some regions of Botswana, South Africa, and Namibia and their associated root bacteria and insect pests. The specific objectives were to (1) identify wild legume species in the target region, (2) assess whether they formed effective N_2 fixation symbioses in nature and isolate and characterise their bacteria, (3) identify pests of legumes and assess the damage they caused, and (4) assess rhizosphere microbiomes along the Kavango River in Namibia.

Methods

Description of study sites

Field surveys were conducted around the Okavango Delta in Botswana, in several regions of Nambia, and in the Northern Cape region of South Africa. Sampling in farmers' fields and in nature was carried out when both herbaceous wild and cultivated legumes were at the peak of flowering. In the Okavango panhandle, the survey was conducted at Seronga (18°50′11″S; 22°18′06″ E), Ngarange

(18°24′31″ S; 22°01′25″ E), and Xakao (18°18′17″ S; 21°53′16″ E). In Namibia, plant surveys were carried out in Kavango Province near Rundu and Mashare, in the Kunene region near the Grootberg Pass, and in the Omaheke region near Gobabis. All of the sites in the three countries where legume surveys were undertaken are covered by Kalahari aeolian sand deposits, and hence the soils are very sandy with very low fertility, low soil moisture, and high soil temperatures (Schulze & Kruger, 2007; Grönemeyer et al., 2014; Bernard et al., 2017).

Plant sampling

At each of the sites in Botswana, grain legumes were sampled from farmers' fields by digging them up with intact roots and nodules. In the wild, herbaceous legumes were sampled from within a radius of 50 m at each of the sites (Botswana), at smallholders' fields near Mashare (Namibia), or at natural sites free of cropping (Namibia, South Africa). Plants from Botswana were identified by the BUAN Herbarium, from Namibia by NBRI (Leevon Nanyeni) and from South Africa by Ute Schmiedel.

Insect sampling and damage assessment

Insects associated with herbaceous legumes were sampled and the incidence of damage on the plants assessed in Botswana. At each location, 20 herbaceous leguminous plants per species were randomly sampled in an area covering 40 m^2 at each of the above-mentioned villages. The insect infestation was assessed above and below the ground. The assessment of insect damage on foliage was done using in situ counts. To assess the infestation by soil-dwelling insects, plants were dug up with intact roots and inspected for the presence of insects and damage. Tiny insects were observed under the microscope and larger ones with the naked eye. The assessment was based on the number of insects per plant, proportion of plants damaged, and severity of damage based on symptoms. The insects collected were identified to taxonomic class, order, family, and species where possible. In this paper, we report only on the jewel beetle (*Sphenoptera* sp.) because it was the most widely distributed.

Table 1: Nodulated herbaceous legumes detected in Botswana

Okavango	Tswapong	Kgalagadi
Indigofera flavicans Baker	*Zornia glochidiata* DC.	*Indigofera* spp.
Indigofera tinctoria L.	*Chamaecrista bieinsis* (Stey.) Lock	*Cyamopsis dantata* (N.E. Br.) Torre
Chamaecrista biensis (Stey.) Lock		*Cullen tometosum* (Thunb.) J.W. Grimes
Indigofera astragalina DC.	*Vigna unguiculata* subsp. *dekindtiana* (Harms) Verdc.	*Arachis hypogea* L.
Indigofera daeloides Harv.	*Chamaecrista absus* (L.) Irwin and Barneby	*Vigna unguiculata* (L.) Walp
Tephrosia purpurea Pers.	*Tephrosia purpurea* Pers.	*Vigna subterranean* (L.) Verdc.
Tephrosia lupinifolia DC.	*Rhyncosia totta* DC.	
Chamaecrista absus (L.) Irwin and Barneby	*Arachis hypogea*	
Crotalaria astragalina Hochst.	*Vigna unguiculata* (L.) Walp	
Crotalaria sphaerocarpa DC.	*Vigna subterranean* (L.) Verdc.	
Crotalaria pisicarpa Baker		
Vigna unguiculata subsp. *dekindtiana* (Harms) Verdc.		
Rhyncosia totta DC.		
Zornia glochidiata DC.		
Arachis hypogea L.		
Vigna unguiculata (L.) Walp		
Vigna subterranean (L.) Verdc.		

Table 2: Nodulated wild legumes detected in South Africa and Namibia

South Africa, Northern Cape	Namibia, Kavango	Namibia, Omaheke
Leobordea digitata (Harv.) B.-E. van Wyk & Boatwr.	*Chamaecrista absus* (L.) Irwin and Barneby	*Indigofera alternans* DC.
Leobordea polycephala (E. Mey.) B.-E. van Wyk & Boatwr.	*Chamaecrista biensis* (Stey.) Lock	*Indigofera flavicans* Baker
	Chamaecrista sp.	
	Crotolaria flavicarinata Baker f.	
Lotononis falcata (E. Mey.) Benth.	*Crotolaria heidmanii* Schinz	*Tephrosia burchellii* Burtt Davy
Lotononis leptoloba Bolus	*Crotalaria podocarpa* DC.	*Tephrosia dregeana* E. Mey.
Medicago laciniata (L.) Mill.	*Crotalaria platysepala* Harv.	
Medicago polymorpha L.	*Crotalaria sphaerocarpa* DC.	
Wiborgia monoptera E. Mey.	*Indigastrum parviflorum* Jaub. & Spach	**Namibia, Kunene**
Lessertia diffusa R. Br.	*Indigofera astragalina* DC.	*Crotalaria podocarpa* DC.
	Indigofera charlieriana Schinz	*Indigofera auricoma* E. Mey.
	Indigofera rautanenii Baker f.	
Lessertia capitata E. Mey.	*Rhynchosia venulosa* (Hiern) K. Schum.	
	Tephrosia burchelii Burtt Davy	
	Tephrosia dregeana E. Mey.	
	Zornia glochidata DC.	

Isolation and characterisation of root nodule and rhizosphere bacteria

Root nodules were transported to the laboratory under dried conditions with silica gel dessicant (Grönemeyer et al., 2013), and bacteria were isolated and characterised from root nodules using standard procedures (Vincent, 1970;Grönemeyer et al., 2013). Briefly, the bacterial isolation procedure was as follows: After the soil had been removed from the nodules, they were immersed for 10 s in 70% ethanol, followed by immersion in 3% sodium hypochlorite for 2–3 min depending on the size of the nodule, and then rinsed 10 times in sterile distilled water. Each nodule was dissected with a blade and squashed with forceps. The milky liquid from the nodules was plated on yeast mannitol agar and incubated at 28°C for about 15 days. Plates were checked daily and new growth reported. After pure colonies had been isolated, bacteria were plated on different media to assess their phosphate solubilisation, siderophore production, and cellulase activity. Bacteria were also isolated from the rhizosphere of indigenous legumes using standard procedures in Namibia (Kandjimi et al., 2015).

Authentication of bacterial isolates

To satisfy Koch's postulates, bacteria were authenticated on their homologous hosts under sterile conditions in the greenhouse. Eleven isolates were tested for their ability to form root nodules on *Crotalaria sphaerocarpa*. Seeds were sterilised by immersion for 3 min in household bleach solution (3% NaOCl), followed by 12 rinses in sterile distilled water and soaking in the last rinse for 2 h. The sterilised seeds were then placed on 1% water agar and incubated at 28ºC for 2 d to produce seedlings. The seedlings of *C. sphaerocarpa* were raised in sterile autoclaved sand pots under greenhouse conditions. Two seedlings were planted in the pot and inoculated with 1 mL of bacterial cells suspended in sterile distilled water. Three pots per strain were inoculated. Plants were fed with N-free Hoagland solution twice a week and were grown for up to 5 weeks. For each strain, a negative control without fertiliser and inoculation and a positive control with 5 mM of potassium nitrate were included. At harvest, each plant was separated into shoots, roots, and nodules. The shoots and roots were dried at 60ºC for 48 h and weighed on a balance to determine their dry matter.

Table 3: Bacteria species isolated from grain and indigenous legume species from Okavango Delta and Tswapong region in Botswana

Bacteria with Highest Similarity from NCBI BLAST	Host Legume Plant	Place of Origin
Bacillus acidiceler	*Vigna unguiculata*	Mmoo Kokonye
Rhizobium tropici	*Vigna unguiculata* subsp. *dekindtiana*	Xakao
Brevibacilllus brevis	*Crotalaria sphaerocarpa*	Ngarange
Bacillus acidiceler	*Vigna unguiculata* subsp. *dekindtiana*	Qabo
Rhizobium sp.	*Arachis hypogaea*	Lekobeng
Pseudomonas aeruginosa	*Arachis hypogaea*	Mmoo Kokonye)
Brevibacillus agri strain	*Vigna unguiculata*	Mmoo Kokonye
Brevibacillus brevis	*Vigna subterranea*	Lekadiba

DNA sequencing of root nodule bacteria

The 16S rDNA gene fragment was amplified using universal bacterial 16S primers 27f (5'-AGAGTTGATCCTGGCTCAG-3') and 1492r (5'-GGTTACCTTACGACTT-3') (Lane, 1991). The names of the primers denote the positions of their recognition sites on the 16S rDNA gene. The 16S rDNA amplicons were sent to Inqaba Laboratories (Pretoria, South Africa) for sequencing.

Results

Diversity of herbaceous legumes

Table 1 presents the results of the legume survey that was undertaken in the Okavango Delta and the Tswapong region. In both cases the survey was conducted at four locations. Table 1 shows that more herbaceous legume plant species were found in the higher-rainfall Okavango Delta compared to Tswapong area. In Namibia and South Africa, a broad range of wild legumes were found, 33 plant types were nodulated at their natural sites, and most of them could be taxonomically identified (Tab. 2). This is the first report of nodulation of these wild legumes in these areas of Botswana, Namibia, and South Africa. Several species were commonly found in the different surveys (Tab. 1 and 2) in the Kavango region of Namibia and Botswana, such as *Chamaecrista bieinsis* (Stey.) Lock, *Chamaecrista absus* (L.) Irwin and Barneby, *Zornia glochidata* DC., and several *Crotalaria* and *Indigofera* species. Root nodule bacteria were isolated and characterized for some plants (Tab. 3).

Authentication of root nodule bacteria

Table 3 shows the authentication of root nodule bacterial isolates on *Crotalaria sphaerocarpa* (DC.) Benth. under sterile greenhouse conditions. The various isolates come from root nodules of *C. sphaerocarpa* from Lekadiba (LKD) in Tswapong, Ngarange (NGA), Qabo (QAB), Grootlagte (GRT), and Xauga in the Okavango Delta. Eight out of eleven isolates were authenticated as rhizobia since they formed N_2-fixing root nodules on their homologous host. Some rhizobia such as strain BUAN316/XAU-Sc70B induced biomass production similar to 5 mM of potassium nitrate. Interestingly, some non-N_2-fixing strains — for example, BUAN316/NGA-Cs7C — were able to induce plant growth better than some N_2-fixing strains such as BUAN316/LKD-Cs4.

Diversity of root nodule bacteria isolated from herbaceous legumes

The majority of the bacteria isolated from the root nodules of herbaceous legumes sampled from various regions in Botswana showed that few were rhizobia (Tab. 4). Their 16S rDNA identified them as belonging to the genera *Bacillus* and *Brevibacillus*. *Rhizobium tropici* was isolated from *Vigna unguiculata* subsp. *dekindtiana*.

Table 4: Bacteria species isolated from identified indigenous legume species along Kavango River, Namibia

Isolate number	Bacteria with Highest Similarity from NCBI BLAST	Host Legume Plant	Place of Origin
3	*Shigella flexneri*	*B. petersiana*	Mabushe
4	*Acinetobacter pitti*	*Acacia hebeclada*	Nkurenkuru
5	*Bacillus aryabhattai*	*B. petersiana*	Nkurenkuru
8	*Ochromobacterium intermedium*	*B. petersiana*	Mabushe
9	*Azospirillum oryzae*	*B. petersiana*	Mabushe
11	*Klebsiella oxytoca*	*A. hebeclada*	Nkurenkuru
12	*Ochromobacterium intermedium*	*A. hebeclada*	Mashare
13	*Acinetobacter pitti*	*A. hebeclada*	Mashare
14	*Lysinibacillus pakistanensis*	*A. erioloba*	Katwitwi
15	*Trabulsiella guamensis*	*A. erioloba*	Katwitwi
21	*Brevibacillus reuszeri*	*A. hebeclada*	Mashare
25	*Pseudomonas xanthomarina*	*A. erioloba*	Katwitwi
30	*Enterobacter cloacae* subsp. *dissolvens*	*Brachystegia boehmii*	Katwitwi
40	*Arthrobacter oxydans*	*B. petersiana*	Mabushe
52	*Bacillus vallismortis*	*B. petersiana*	Mabushe
55	*Streptomyces* sp.	*B. petersiana*	Mashare
64	*Brevibacillus formosus*	*A. erioloba*	Rundu
66	*Bacillus aryabhattai*	*A. erioloba*	Mabushe

Similarly, various bacteria from different genera such as *Bacillus*, *Ochromobacterium*, *Pseudomonas*, and *Brevibacillus* were isolated from the rhizosphere of leguminous shrubs and trees in Namibia (Tab. 4).

Insect incidence and damage

The flat-headed borer, *Sphenoptera* sp. [Buprestidae: Chrysochroinae] was widely distributed across the study areas, having been collected from the Tswapong, Kgalagadi South, Okavango, and Gantsi regions of Botswana. *Sphenoptera* sp. beetles were collected from the roots of *Crotalaria sphaerocarpa, C. diateri, T. pumila, T. dregeana, T. lupinifolia*, and *Indigofera* sp. It was recorded on *C. absus* and *Senna obtusifolia* during this study. The highest percentage of plants damaged was recorded at Lecheng on *Indigofera* sp. The infestation also differed between plant species. The highest infestation was on *C. sphaerocarpa,* followed by *Tephrosia* sp. and *Indigofera* spp. The larval stage of the *Sphenoptera* jewel beetle bored into stems and tunneled into root systems (Fig. 1).

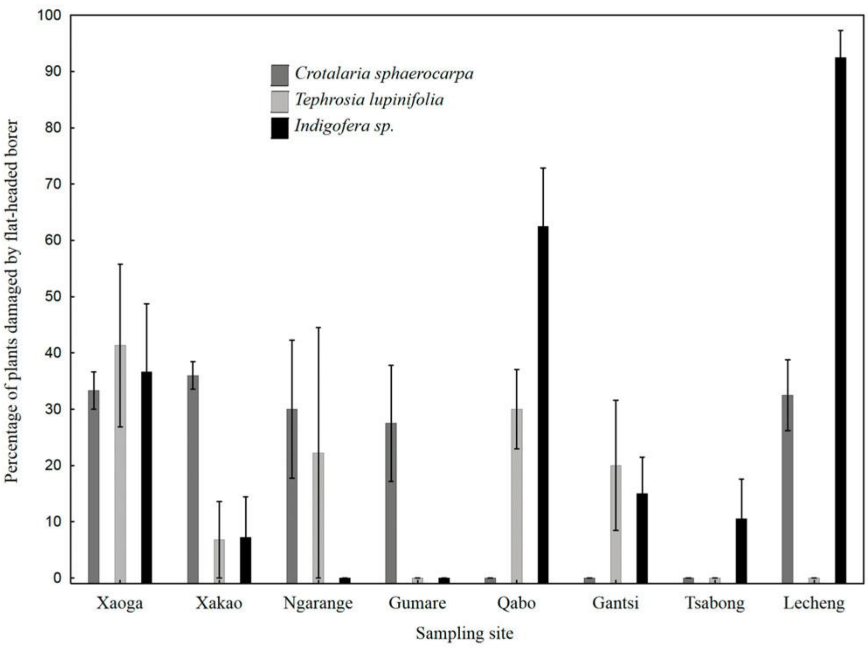

Figure 1: Percentage of plants damaged by flat-headed borers at the different study sites.

Discussion

The predominant agriculture paradigm based on improved varieties of common staple crops in high-input systems has not succeeded in addressing food insecurity and malnutrition in places such as sub-Saharan Africa (Rudebjer et al., 2013), where over 200 million people (28% of the population) were undernourished in 2005–2007 (FAO, 2010). Yield variability and risk for crop failure in Africa's rainfed agriculture systems contribute to factors that explain difficulties in adopting new technologies (Ogada et al., 2010). This will even become more problematic as climate change leads to a decline in land area suitable for the cultivation of crops under dryland conditions in Sub-Saharan Africa (Lane & Jarvis, 2007). Population pressure and traditional food production through dryland agriculture without nutrient inputs are leading to a reduction of soil carbon pools and available nutrients (Luther-Mosebach et al., 2015) as well as causing soil degradation and increased fire frequency (Carreira et al., 1996).

Diversity of wild herbaceous legumes and N_2 fixation

In this study, we have shown that herbaceous legumes were nodulated (Tab. 1 and 2). Bernard et al. (2017) have shown that in Botswana, the legumes in Table 1 fixed N_2 in their locales. Furthermore, results from the current study indicated that the diversity of legumes decreased with increasing aridity in Botswana. For example, whereas 15 herbaceous species were recorded in the wetter Okavango Delta (rainfall average of over 500 mm), only six were found in the drier Kgalagadi region around Tsabong (rainfall average of about 300 mm). With the increasing effects of climate change, under which southern Africa is predicted to become drier (Serdeczny et al., 2017), the diminishing number of nodulated legumes with aridity has a bearing on nutrient cycling in ecosystems. For example, *Chamaecrista rotundifolia* fixed 144 kg N/ha in Nigeria (Sanginga et al., 2003), *Crotalaria pallida* fixed 173 kg N/ha in Domboshawa in Zimbabwe, both seeded at 120 seeds/m^2 (Nezomba et al., 2008) and fixed 140 kg N/ha in Chinyika in Zimbabwe

(Tauro et al., 2009), and *Sesbania sesban* could fix between 43 and 102 kg N/ha in Senegal (Ndoye & Dreyfus, 1988). In Botswana, studies on the amount of N_2 fixed per hectare of herbaceous legumes are scarce. In the study by Bernard et al. (2017), an estimation of N-fixed per plant was made using the natural abundance technique. For example, *Chamaecrista absus* fixed 134.8 mg N/plant while *Tephrosia* sp could fix 143.4 mg N/plant. N_2 fixation is an important process for the sustainable maintenance of soil fertility. The legumes in this study have the potential to be green manures and fodder crop species (see Madibela et al., 2018) because of their N_2 fixing ability. With less rainfall and higher temperatures as predicted by climate change models (Pröpper et al., 2015), it is important to select such crops and plants that can withstand the harsh environmental conditions.

Characteristics and diversity of bacteria isolated from root nodules and the rhizosphere of legumes

During the plant surveys, root nodules were collected and bacteria were isolated from them. In Botswana, the reason for isolating bacteria was to prospect for elite rhizobial strains with the potential for development into inoculants. It is noteworthy that most of the bacteria isolated from the root nodules of herbaceous legumes harvested from the wild were not rhizobia, but instead mostly species of *Bacillus* and *Brevibacillus*, known plant growth–promoting bacteria (Tab. 3). Interestingly, when examined, the nodules were pinkish red in their interior, showing the presence of leghaemoglobin. It is possible that the rhizobia enter a viable but not culturable (VBNC) state. Bacterial cells enter the VBNC state as a response to some form of natural stress, such as starvation, incubation outside the temperature range of growth, elevated osmotic concentrations (e.g., seawater), oxygen concentration, or exposure to white light (Oliver, 2000). It is not clear whether most rhizobia enter into VBNC during stress periods since Oliver (2005) listed only *Rhizobium leguminosarum* and *Sinorhizobium meliloti* as being capable of entering the VBNC state. What is clear is that in addition to rhizobia, root nodules harbour other bacteria that promote plant growth in different ways. For example, *Brevibacillus brevis* has been shown to promote growth in cotton through positive traits such as indole-3-acetic acid (IAA), acetylene reduction assay (ARA), antifungal activity, and ammonia production (Nehra et al., 2016). In Table 5, some non-rhizobial bacterial strains have been shown to promote plant growth. For example, BUAN316/LKD-Cs4, an N_2-fixing strain, induced significantly less biomass compared to BUAN316/NGA-Cs7C, a non-rhizobial strain. What needs to be ascertained is the mechanism through which plant growth is promoted. In Namibia, a number of bacteria were isolated from the roots of some nodulated and non-nodulated leguminous plants (Tab. 4). Some of the listed bacteria such as species of *Brevibacillus, Bacillus*, and *Arthrobacter* have been shown to have various traits of plant growth promotion (de Souza et al., 2015).

The potential of biological nitrogen fixation (BNF) that can be realized in nitrogen-fixing symbioses between legumes and rhizobia can be applied for a more sustainable agricultural practice. Current research and extension efforts need to be directed towards an integrated nutrient management approach in which legumes play a crucial role. Inoculation with compatible rhizobia resistant to harsh environmental conditions can make BNF a key resource for farmers with little income (Smaling et al., 2008). Legumes or pulses can provide protein- and nutrient-rich food and feed, providing marketable products and a long-lasting value chain. Furthermore, plant residues of nitrogen-fixing legumes, if added to soil, enhance nitrogen status and organic matter content in intercropping and crop rotation schemes.

Insect incidence and damage

In addition to the soil fertility issue, pests such as stemborers are a real challenge. The prevalence of and damage by the widely distributed flat-headed borer (*Sphenoptera* spp.) on the roots of wild herbaceous legumes negatively affect these plants' biological nitrogen-fixing efficiency and reduce their biomass

Table 5: Nodulation and dry matter of *Crotalaria sphaerocarpa* during authentication of bacterial strains

Strain	Nod	N_2 Fix	Shoot DM ($g.plant^{-1}$)	Root DM ($g.plant^{-1}$)	Nodules $plant^{-1}$	Nodule weight ($mg.plant^{-1}$)
BUAN316/LKD-Cs4	+	+	0.10 ± 0.02bc	0.01 ± 0.00cd	4.00 ± 0.88cd	13.30 ± 3.34b
BUAN316/LKD-Cs6	+	+	0.33 ± 0.08abcd	0.01 ± 0.00cd	5.00 ± 0.67cd	16.70 ± 5.78b
BUAN316/NGA-Cs7C	-	+	0.18 ± 0.05bdc	0.01 ± 0.00cd	0.00 ± 0.00e	0.00 ± 0.00c
BUAN316/QAB-Cs36	+	-	0.02 ± 0.01d	0.01 ± 0.00cd	2.00 ± 0.33cd	5.00 ± 0.00b
BUAN316/QAB-Cs36*	-	-	0.19 ± 0.04bcd	0.04 ± 0.00ab	0.00 ± 0.00e	0.00 ± 0.00c
BUAN316/NGA-Cs38	+	+	0.37 ± 0.11abc	0.03 ± 0.01abcd	13.00 ± 3.67b	46.70 ± 12.03b
BUAN316/GRT-Cs52	+	+	0.36 ± 0.07abc	0.03 ± 0.01abcd	5.00 ± 0.33cd	30.00 ± 5.78b
BUAN316/GRT-Cs52*	-	-	0.15 ± 0.02bcd	0.01 ± 0.00cd	0.00 ± 0.00e	0.00 ± 0.00c
BUAN316/XAU-Cs68B	+	+	0.30 ± 0.03abcd	0.05 ± 0.01a	26.00 ± 2.91a	650.00 ± 276.08a
BUAN316/XAU-Cs70A	+	+	0.26 ± 0.07bcd	0.02 ± 0.00bcd	6.00 ± 1.15c	43.30 ± 8.83b
BUAN316/XAU-Cs70B	+	+	0.46 ± 0.09ab	0.04 ± 0.01ab	8.00 ± 1.73c	50.00 ± 5.78b
BUAN316-CsC	+	-	0.63 ± 0.12a	0.03 ± 0.00abc	0.00 ± 0.00e	0.00 ± 0.00c
BUAN316-CsC	-	-	0.11 ± 0.02cd	0.02 ± 00bcd	0.00 ± 0.00e	0.00 ± 0.00c
F statistics			**6.44*** **	**2.22***	**24.05*** **	**4.72** **

production. Direct feeding on root nodules by *Sphenoptera* sp. was not established, and currently no literature attests to that. However, feeding on root systems may affect the physiology of the plants and consequently interfere with a legume's ability to fix nitrogen, as in case of nodule-feeding weevils, *Stona* spp. (Quinn & Hower, 1986). Feeding on the roots may reduce translocation of water and nutrients up the plants, consequently reducing the biomass needed for livestock feed.

Here we identified a broad range of wild legumes which were reported for the first time to be nodulated in Botswana, Namibia, and South Africa. In Botswana, data on the diversity of wild herbaceous legumes suggested that diversity decreased with increasing aridity. Our data have also shown that the majority of the inhabitants of the root nodules were not rhizobia, leading to the suggestion that they were in a state of VBNC. Furthermore, known plant growth–promoting bacteria such as species of *Bacillus* and *Brevibacillus* were common in the root nodules of herbaceous legumes. Finally, the flat-headed jewel beetle (*Sphenoptera* sp.) caused a lot of damage on herbaceous legumes, suggesting that if some of the plants were to be developed into fodder crops in the future, pest control would be needed.

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References

Amoako-Atta, B., Emolo, E.O. & Kidega, E.K. (1983) Influence of maize, cowpea and sorghum intercropping systems on stem-/pod-borer infestations. *International Journal of Tropical Insect Science*, **4**, 39–46.

Bernard, N., Losologolo, M., Batlang, U., Ngwako, S., Mashungwa, G.N., Tselaesele, N.M. & Pule-Meulenberg, F. (2017) Symbiotic performance of grain and wild herbaceous legumes in the Okavango Delta and Tswapong region of Botswana. *Symbiosis*, 1–10.

Burbano, C.S., Grönemeyer, J.L., Hurek T. & Reinhold-Hurek, B. (2015) Microbial community structure and functional diversity of nitrogen-fixing bacteria associated with *Colophospermum mopane*. *FEMS Microbiology Ecology*, **91**, fiv030. doi:10.1093/femsec/fiv1030

Carreira, J.A., Arevalo, J.R. & Niell, F.X. (1996) Soil degradation and nutrient availability in fire-prone Mediterranean shrublands of south-eastern Spain. *Arid Land Research and Management*, **10**, 53–64.

Chianu, J.N., Nkonya, E.M., Mairura, F.S., Chianu, J.N. & Akinnifesi, F.K. (2011) Biological nitrogen fixation and socioeconomic factors for legume production in Sub-Saharan Africa. *Sustainable agriculture 2* (ed. by E. Lichtfouse, M. Hamelin, M. Navarrete and P. Debaeke), pp. 309–329. Springer, Dordrecht.

Chimwamurombe, P.M., Grönemeyer, J.L. & Reinhold-Hurek, B. (2016) Isolation and characterization of culturable seed-associated bacterial endophytes from gnotobiotically grown Marama bean seedlings. *FEMS Microbiology Ecology*, **92(6)**, fiw083. http://dx.doi.org/10.1093/femsec/fiw1083

FAO (2010) *The state of food insecurity in the world. Addressing food insecurity in protracted crises.* Food and Agriculture Organization of the United Nations, Rome, Italy.

Gao, Y., Yu, G., Luo, C. & Zhou, P. (2012) Groundwater nitrogen pollution and assessment of its health risks: a case study of a typical village in rural-urban continuum, China. *PLOS One*, **7(4)**, e33982. doi:10.1371/journal.pone.0033982

Grönemeyer, J., Berkelmann, D., Mubyana-John, T., Haiyambo, D., Chimwamurombe, P., Kasaona, B., Hurek, T. & Reinhold-Hurek, B. (2013) A survey for plant-growth-promoting rhizobacteria and symbionts associated with crop plants in the Okavango region or Southern Africa. *Biodiversity & Ecology*, 5, 287–294.

Grönemeyer, J.L., Burbano, C.S., Hurek, T. & Reinhold-Hurek, B. (2012) Isolation and characterization of root-associated bacteria from agricultural crops in the Kavango region of Namibia. *Plant Soil*, **356**, 67–82.

Grönemeyer, J.L., Kulkarni, A. Berkelmann, D., Hurek, T. & Reinhold-Hurek, B. (2014) Identification and characterization of rhizobia indigenous to the Okavango region in Sub-Saharan Africa. *Applied and Environmental Microbiology*, **80**, 7244–7257.

Gröngröft, A., Luther-Mosebach, J., Landschreiber, L. & Eschenbach, A. (2013) Cusseque Soils. *Biodiversity & Ecology*, **5**, 51–54.

Kandjimi, O.S., Uzabakiriho, J.D. & Chimwamurombe, P.M. (2015) Isolation and characterization of culturable bacteria from bulk soil samples and the rhizosphere of arid-adapted *Tylosema esculentum* (Burchell) A. Schreiber (Marama bean) in Namibia. *African Journal of Biotechnology*, **14**, 944–952.

Lane, A. & Jarvis, A. (2007) Changes in climate will modify the geography of crop suitability: agricultural biodiversity can help with adaptation. *SAT eJournal ICRISAT*, **4**, 1–12.

Lane, D. J., 1991. 16S/23S sequencing. In Stackebrandt, E., and Goodfellow, M. (Eds.). Nucleic acid techniques in bacterial systematics. John Wiley & Sons, Inc. New York, pp. 115–175.

Linquist, B.A., Adviento-Borbe, M.A., Pittelkow, M., van Kessel, C. & van Groenigen, K.J. (2012) Fertilizer management practices and greenhouse gas emissions from rice systems: a quantitative review and analysis. *Field Crops Research*, **135**, 10–21.

Luther-Mosebach, J., Gröngröft, A. & Eschenbach A**.** (2015) Influence of landscape and land-use on the soil sarbon stocks in the Okavango Catchment. *Böden im Wandel* (ed. by C. Knoblauch, C. Fiencke and K. Berger), pp. 155–166. Verein zur Förderung der Bodenkunde Hamburg 77. University of Hamburg, Hamburg, Germany.

Madibela, O.R., Kemiso, D. & Kwedibana, J. (2018) Quality of wild herbaceous legumes and its role in livestock nutrition. This volume.

Ndoye, I., Dreyfus, B., 1988. N_2 fixation by *Sesbania rostrata* and *Sesbania sesban* using ^{15}N and total N difference methods. Soil Biology & Biochemistry, **20**, 209-213.

Nehra, V., Saharan, B.S. & Choudhary, M. (2016) Evaluation of *Brevibacillus brevis*. *SpringerPlus*, **5**, 1–10.

Nezomba, H., Tauro, T.P., Mtambanengwe, F. & Mapfumo, P. (2008) Nitrogen fixation and biomass productivity of indigenous legumes for fertility restoration of abandoned soils in smallholder farming systems. *South African Journal of Plant and Soil*, **25**, 161–171.

Ogada, M.J., Nyangena, W. & Yesuf, M. (2010) Production risk and farm technology adoption in the rainfed semi-arid lands of Kenya. *African Journal for Agricultural and Resource Economics*, **4**, 159–174.

Oliver, J. D. (2000). Problems in detecting dormant (VBNC) cells, and the role of DNA elements in this response. Tracking genetically-engineered microorganisms. Landes Biosciences, Georgetown, Tex, pp 1-15.

Oliver, J. D. (2005). The viable but nonculturable state in bacteria. The Journal of Microbiology, **43**, 93-100.

Pröpper, M., Gröngröft, A., Finckh, M., Stirn, S., De Cauwer, V., Lages, F., Masamba, W., Murray-Hudson, M., Schmidt, L., Strohbach, B. & Jürgens, N. (2015) *The future Okavango: findings, scenarios and recommendations for action.* University of Hamburg, Hamburg.

Pule-Meulenberg, F. & Dakora, F.D. (2007). Assessing the biological potential of N_2-fixing Leguminosae in Botswana for increased crop yields and commercial exploitation. *African Journal of Biotechnology*, **6**, 325–334.

Pule-Meulenberg, F. & Dakora, F.D. (2009) Assessing the symbiotic dependency of grain and tree legumes on N_2 fixation for their N nutrition in five agro-ecological zones of Botswana. *Symbiosis*, **48**, 68–77.

Quinn, M. A. and Hower , A. A. (1986). Effects of root nodules and taproots on survival and abundance of *Sitona hispidulus* (Coleoptera: Curculionidae) on *Medicago sativa. Ecological Entomology,* **11**, 391–400

Rudebjer, P., Chakeredza, S., Dans, A., Ekaya, W., Ghezae, N., Aboagye, L.N., Kwapata, M., Njoroge, M. & Padulosi, S. (2013) Beyond commodity crops: Strengthening young scientists' capacity for research on underutilized species in Sub-Saharan Africa. *Acta Horticulturae*, **979**, 577–589.

Sanginga, N., Dashiell, K.E., Diels, J., Vanlauwe, B., Lyasse, O., Carsky, R.J., Tarawali, S., Asafo-Adjei, B., Menkir, A., Schulz, S. & Singh, B.B., (2003). Sustainable resource management coupled to resilient germplasm to provide new intensive cereal–grain–legume–livestock systems in the dry savanna. Agriculture, Ecosystems & Environment, **100**, 305-314.

Food security

Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Robinson, A., Hare, W., Schaeffer, M., Perrette, M. & Reinhardt, J. (2017) Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Regional Environmental Change*, **17**, 1585–1600.

Schulze, R.E. & Kruger, G.P. (2007) Terrain methodology. *South African atlas of climatology and agrohydrology*, pp. 13–16.

Smaling, E.M.A., Roscoe, R., Lesschen, J.P., Bouwman, A.F. & Comunello, E. (2008) From forest to waste: assessment of the Brazilian soybean chain, using nitrogen as a marker. *Agriculture, Ecosystems & Environment*, **128**, 185–97.

de Souza, R., Meyer, J., Schoenfeld, R., da Costa, P. B., & Passaglia, L. M. (2015). Characterization of plant growth-promoting bacteria associated with rice cropped in iron-stressed soils. Annals of microbiology, **65**, 951-964.

Tauro, T.P., Nezomba, H., Mtambanengwe, F. & Mapfumo, P. (2009) Germination, field establishment patterns and nitrogen fixation of indigenous legumes on nutrient-depleted soils. *Symbiosis*, **48**, 92–101.

Wisch, U., Petersen, A., Gröngröft, A. & Eschenbach, A. (2009) Dryland farming in the Kavango region: effect of land use on soil properties. *Zentralblatt für Geologie und Paläontologie*, **1**, 189–211.

Yanggen, D., Kelly, V., Reardon, T. & Naseem, A. (1998) Incentives for fertilizer use in Sub-Saharan Africa: A review of empirical evidence on fertilizer response and profitability. International Development Working Paper 70. Department of Agricultural Economics, Michigan State University, East Lansing, MI, USA.

References [CrossRef]

Amoako-Atta, B., Emolo, E.O. & Kidega, E.K. (1983) Influence of maize, cowpea and sorghum intercropping systems on stem-/pod-borer infestations. *International Journal of Tropical Insect Science*, **4**, 39–46. CrossRef

Bernard, N., Losologolo, M., Batlang, U., Ngwako, S., Mashungwa, G.N., Tselaesele, N.M. & Pule-Meulenberg, F. (2017) Symbiotic performance of grain and wild herbaceous legumes in the Okavango Delta and Tswapong region of Botswana. *Symbiosis*, 1–10. CrossRef

Burbano, C.S., Grönemeyer, J.L., Hurek T. & Reinhold-Hurek, B. (2015) Microbial community structure and functional diversity of nitrogen-fixing bacteria associated with *Colophospermum mopane*. *FEMS Microbiology Ecology*, **91**, fiv030. CrossRef

Carreira, J.A., Arevalo, J.R. & Niell, F.X. (1996) Soil degradation and nutrient availability in fire-prone Mediterranean shrublands of southeastern Spain. *Arid Land Research and Management*, **10**, 53–64. CrossRef

Chianu, J.N., Nkonya, E.M., Mairura, F.S., Chianu, J.N. & Akinnifesi, F.K. (2011) Biological nitrogen fixation and socioeconomic factors for legume production in Sub-Saharan Africa. *Sustainable agriculture 2* (ed. by E. Lichtfouse, M. Hamelin, M. Navarrete and P. Debaeke), pp. 309–329. Springer, Dordrecht.

Chimwamurombe, P.M., Grönemeyer, J.L. & Reinhold-Hurek, B. (2016) Isolation and characterization of culturable seed-associated bacterial endophytes from gnotobiotically grown Marama bean seedlings. *FEMS Microbiology Ecology*, **92(6)**, fiw083. CrossRef

FAO (2010) *The state of food insecurity in the world. Addressing food insecurity in protracted crises.* Food and Agriculture Organization of the United Nations, Rome, Italy.

Gao, Y., Yu, G., Luo, C. & Zhou, P. (2012) Groundwater nitrogen pollution and assessment of its health risks: a case study of a typical village in rural-urban continuum, China. *PLOS One*, **7(4)**, e33982. CrossRef

Grönemeyer, J., Berkelmann, D., Mubyana-John, T., Haiyambo, D., Chimwamurombe, P., Kasaona, B., Hurek, T. & Reinhold-Hurek, B. (2013) A survey for plant-growth-promoting rhizobacteria and symbionts associated with crop plants in the Okavango region or Southern Africa. *Biodiversity & Ecology*, 5, 287–294. CrossRef

Grönemeyer, J.L., Burbano, C.S., Hurek, T. & Reinhold-Hurek, B. (2012) Isolation and characterization of root-associated bacteria from agricultural crops in the Kavango region of Namibia. *Plant Soil*, **356**, 67–82. CrossRef

Grönemeyer, J.L., Kulkarni, A. Berkelmann, D., Hurek, T. & Reinhold-Hurek, B. (2014) Identification and characterization of rhizobia indigenous to the Okavango region in Sub-Saharan Africa. *Applied and Environmental Microbiology*, **80**, 7244–7257. CrossRef

Gröngröft, A., Luther-Mosebach, J., Landschreiber, L. & Eschenbach, A. (2013) Cusseque Soils. *Biodiversity & Ecology*, **5**, 51–54. CrossRef

Kandjimi, O.S., Uzabakiriho, J.D. & Chimwamurombe, P.M. (2015) Isolation and characterization of culturable bacteria from bulk soil samples and the rhizosphere of arid-adapted *Tylosema esculentum* (Burchell) A. Schreiber (Marama bean) in Namibia. *African Journal of Biotechnology*, **14**, 944–952.

Lane, A. & Jarvis, A. (2007) Changes in climate will modify the geography of crop suitability: agricultural biodiversity can help with adaptation. *SAT eJournal ICRISAT*, **4**, 1–12.

Lane, D. J., 1991. 16S/23S sequencing. In Stackebrandt, E., and Goodfellow, M. (Eds.). Nucleic acid techniques in bacterial systematics. John Wiley & Sons, Inc. New York, pp. 115–175.

Linquist, B.A., Adviento-Borbe, M.A., Pittelkow, M., van Kessel, C. & van Groenigen, K.J. (2012) Fertilizer management practices and greenhouse gas emissions from rice systems: a quantitative review and analysis. *Field Crops Research*, **135**, 10–21. CrossRef

Luther-Mosebach, J., Gröngröft, A. & Eschenbach A. (2015) Influence of landscape and land-use on the soil sarbon stocks in the Okavango Catchment. *Böden im Wandel* (ed. by C. Knoblauch, C. Fiencke and K. Berger), pp. 155–166. Verein zur Förderung der Bodenkunde Hamburg 77. University of Hamburg, Hamburg, Germany.

Madibela, O.R., Kemiso, D. & Kwedibana, J. (2018) Quality of wild herbaceous legumes and its role in livestock nutrition. This volume. CrossRef

Ndoye, I., Dreyfus, B., 1988. N_2 fixation by *Sesbania rostrata* and *Sesbania sesban* using ^{15}N and total N difference methods. Soil Biology & Biochemistry, **20**, 209-213. CrossRef

Nehra, V., Saharan, B.S. & Choudhary, M. (2016) Evaluation of *Brevibacillus brevis*. *SpringerPlus*, **5**, 1–10.

Nezomba, H., Tauro, T.P., Mtambanengwe, F. & Mapfumo, P. (2008) Nitrogen fixation and biomass productivity of indigenous legumes for fertility restoration of abandoned soils in smallholder farming systems. *South African Journal of Plant and Soil*, **25**, 161–171. CrossRef

Ogada, M.J., Nyangena, W. & Yesuf, M. (2010) Production risk and farm technology adoption in the rainfed semi-arid lands of Kenya. *African Journal for Agricultural and Resource Economics*, **4**, 159–174.

Oliver, J. D. (2000). Problems in detecting dormant (VBNC) cells, and the role of DNA elements in this response. Tracking genetically-engineered microorganisms. Landes Biosciences, Georgetown, Tex, pp 1-15.

Oliver, J. D. (2005). The viable but nonculturable state in bacteria. The Journal of Microbiology, **43**, 93-100.

Pröpper, M., Gröngröft, A., Finckh, M., Stirn, S., De Cauwer, V., Lages, F., Masamba, W., Murray-Hudson, M., Schmidt, L., Strohbach, B. & Jürgens, N. (2015) *The future Okavango: findings, scenarios and recommendations for action.* University of Hamburg, Hamburg.

Pule-Meulenberg, F. & Dakora, F.D. (2007). Assessing the biological potential of N_2-fixing Leguminosae in Botswana for increased crop yields and commercial exploitation. *African Journal of Biotechnology*, **6**, 325–334.

Pule-Meulenberg, F. & Dakora, F.D. (2009) Assessing the symbiotic dependency of grain and tree legumes on N_2 fixation for their N nutrition in five agro-ecological zones of Botswana. *Symbiosis*, **48**, 68–77. CrossRef

Quinn, M. A. and Hower , A. A. (1986). Effects of root nodules and taproots on survival and abundance of *Sitona hispidulus* (Coleoptera: Curculionidae) on *Medicago sativa*. *Ecological Entomology*, **11**, 391–400. CrossRef

Rudebjer, P., Chakeredza, S., Dans, A., Ekaya, W., Ghezae, N., Aboagye, L.N., Kwapata, M., Njoroge, M. & Padulosi, S. (2013) Beyond commodity crops: Strengthening young scientists' capacity for research on underutilized species in Sub-Saharan Africa. *Acta Horticulturae*, **979**, 577–589. CrossRef

Sanginga, N., Dashiell, K.E., Diels, J., Vanlauwe, B., Lyasse, O., Carsky, R.J., Tarawali, S., Asafo-Adjei, B., Menkir, A., Schulz, S. & Singh, B.B., (2003). Sustainable resource management coupled to resilient germplasm to provide new intensive cereal–grain–legume–livestock systems in the dry savanna. Agriculture, Ecosystems & Environment, **100**, 305-314. CrossRef

Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Robinson, A., Hare, W., Schaeffer, M., Perrette, M. & Reinhardt, J. (2017) Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Regional Environmental Change*, **17**, 1585–1600. CrossRef

Schulze, R.E. & Kruger, G.P. (2007) Terrain methodology. *South African atlas of climatology and agrohydrology*, pp. 13–16.

Smaling, E.M.A., Roscoe, R., Lesschen, J.P., Bouwman, A.F. & Comunello, E. (2008) From forest to waste: assessment of the Brazilian soybean chain, using nitrogen as a marker. *Agriculture, Ecosystems & Environment*, **128**, 185–97. CrossRef

de Souza, R., Meyer, J., Schoenfeld, R., da Costa, P. B., & Passaglia, L. M. (2015). Characterization of plant growth-promoting bacteria associated with rice cropped in iron-stressed soils. Annals of microbiology, **65**, 951-964. CrossRef

Tauro, T.P., Nezomba, H., Mtambanengwe, F. & Mapfumo, P. (2009) Germination, field establishment patterns and nitrogen fixation of indigenous legumes on nutrient-depleted soils. *Symbiosis*, **48**, 92–101. CrossRef

Wisch, U., Petersen, A., Gröngröft, A. & Eschenbach, A**.** (2009) Dryland farming in the Kavango region: effect of land use on soil properties. *Zentralblatt für Geologie und Paläontologie*, **1**, 189–211.

Yanggen, D., Kelly, V., Reardon, T. & Naseem, A. (1998) Incentives for fertilizer use in Sub-Saharan Africa: A review of empirical evidence on fertilizer response and profitability. International Development Working Paper 70. Department of Agricultural Economics, Michigan State University, East Lansing, MI, USA.

Increasing yields of cereals: benefits derived from intercropping with legumes and from the associated bacteria

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Abstract: Low yield of staple crops such as maize sorghum, pearl millet, and legumes in southern Africa poses a threat to food security, especially in the semi-arid regions of Botswana. The low crop productivity is caused by pests, low fertility, low soil moisture, and high temperatures possibly resulting from climate change. On-farm measurements of N_2 fixation were done in groundnut and Bambara groundnut. Bacteria isolated from their root nodules were assessed as inoculant for cereals under greenhouse conditions. We also determined the most effective sorghum intercrop for reducing yield losses of sorghum caused by stem borers. The results showed that grain legumes fixed N_2 under on-farm conditions. However, amounts of N-fixed on farmers' fields were low because of suboptimal plant densities. Bambara groundnut growing in Lekobeng in Tswapong area fixed the highest amount of nitrogen at 1.3 kg N/ha, a value that is low because of the low planting density used by farmers. Bacteria isolated from legumes showed potential as biofertilisers. For example, in a clayey soil, there were no differences in the number of millet leaves between inoculated and NPK-fed plants. Finally, intercropping of sorghum with legumes led to a reduction in stemborer infestation on sorghum, resulting in higher grain yields for intercrops, about 8.4x more than monocropped sorghum. Taken together, these results show the potential use for legumes and their associated bacteria as biofertilisers in sustainable cropping systems. The data on intercropping will be used to advise farmers on the importance of legume intercrops in controlling stemborers.

Resumo: O baixo rendimento de culturas básicas como o milho, sorgo, milheto e leguminosas na África Austral coloca ameaças à segurança alimentar, em especial nas regiões semi-áridas do Botswana. A baixa produtividade de culturas é causada por pragas, baixa fertilidade, reduzida humidade do solo e elevadas temperaturas, possivelmente devido às alterações climáticas. Em quintas, foram realizadas medições da fixação de N_2 em amendoins e feijão-bambara. Bactérias isoladas dos seus nódulos radiculares foram avaliadas como inoculantes para cereais sob condições de estufa. Também determinámos a intercalação mais eficaz para o sorgo, de modo a reduzir as perdas de rendimento causadas pelas *stemborers* (artrópodes que furam o caule da planta). Os resultados mostraram que as leguminosas fixaram N_2 sob condições agrícolas. No entanto, as quantidades de N fixado nos campos dos agricultores foram baixas devido às densidades insuficientes das plantas. O feijão-bambara em Lekobeng, na área de Tswapong, fixou a maior quantidade de N, 1,3Kg N/ha, um valor que é baixo devido à baixa densidade de plantação utilizada pelos agricultores. As bactérias isoladas de leguminosas mostraram potencial como biofertilizante. Por exemplo, num solo argiloso, não existiram diferenças no número de folhas de milhete entre plantas inoculadas e plantas alimentadas com NPK. Por fim, o cultivo alternado de sorgo com leguminosas levou a uma redução na infestação de *stemborer* no sorgo, levando a maiores rendimentos, cerca de 8,4x mais que em sorgo em monocultura. No conjunto, demonstrámos o potencial uso das leguminosas e suas bactérias, associadas a sistemas de cultivo sustentáveis, como biofertilizantes. Os dados sobre o cultivo alternado serão utilizados para aconselhar os agricultores sobre a importância da intercalação de leguminosas no controlo das *steamborers*.

Introduction

Suboptimal production of staple crops such as maize, sorghum, and pearl millet and pulses such as *Vigna unguiculata* (L.) Walp (cowpea), *Vigna subterannea* (L.) Verdc. (Bambara groundnut), and *Arachis hypogea* L. (groundnut) is the single most worrisome factor negatively affecting food security in Botswana (Statistics Botswana, 2016). This situation is caused and compounded by a variety of factors including drought, poor soils, pests, and diseases (Khan et al., 2008; Mace et al., 2013). Suboptimal farm management practices include low planting densities; use of unadapted crop varieties that are susceptible to pests, diseases, and parasitic weeds; unfavourable planting dates; and injudicious use of inorganic fertilisers. The use of leguminous plants is a possible solution to low soil fertility, especially in low-input farming systems, while resistant varieties can be used to reduce yield losses caused by pests. The relationship between legumes and microorganisms such as bacteria and fungi forms the basis for why legumes are considered important in both natural and agricultural ecosystems. For example, during the biological nitrogen fixation process, bacteria benefit from the carbon energy source fixed by the plant while the plant gets fixed N from the bacteria in return. Biological nitrogen fixation is one of the most studied plant growth–promoting (PGP) processes. Other established plant growth–promoting mechanisms include phosphate solubilisation, iron sequestration through siderophore production and modulating phytohormone levels in the rhizosphere of legumes or non-legumes (Glick, 2012).

Traditionally, soil fertility problems are corrected through fertiliser application whereas those of low soil moisture are solved by irrigation and pests are removed by use of chemical pesticides. Apart from the fact that fertilisers and pesticides are expensive, their application is often associated with exacerbating effects of climate change.

Besides plant growth promotion through the use of various bacteria, intercropping of cereals with legumes reduces pests and consequently improves yields of cereals. For example, sorghum yields per hectare are low and unpredictable, fluctuating largely because of drought, poor soils, and pests (Van den Berg, 1994). Yield losses associated with pests in Africa reportedly range between 25% and 50% (Teetes, 1985). Stemborers are considered major pests of sorghum in many areas where sorghum is produced (Kfir et al., 2002). A survey conducted by Obopile & Mosinkie (2001) showed that famers in Botswana ranked stemborers as the most damaging pests, and losses of up to 10% per larva per plant have been reported (Roome, 1970; Obopile & Mosinkie, 2001). The species of stemborers occurring in Botswana are the spotted stemborer (*Chilo partellus* Swinhoe), the widely distributed African maize stemborer (*Busseola fusca* Fuller), the pink stemborer (*Sesamia calamistis* Hampson) and the sugarcane stemborer (*Eldana saccharina* Walker) (Obopile & Mosinkie, 2001). The objectives of this study were (1) to assess levels of nitrogen fixation and amounts of N_2 fixed by Bambara groundnut and groundnut in farmers' fields in the Okavango delta and Tswapong areas of Botswana, (2) to evaluate the effects of inoculating millet in Botswana with bacteria isolated from root nodules and roots of herbaceous legumes under glasshouse conditions, and (3) to determine the most effective sorghum intercrop that will reduce yield losses caused by stem borers on sorghum.

Materials and methods

Study site and sampling design

The sampling of groundnut and Bambara groundnut plants was done at Xakao (18°18′17″ S; 21°53′16″ E) in the Okavango Delta and at Lekobeng (22°44′16″ S; 27°11′17″ E) in the Tswapong region of Botswana. At each location, four plants were sampled randomly in an area measuring about 20 m x 20 m that was subdivided into 4 strata, with each stratum representing a replication. Therefore, a total of 16 plants were sampled from each field.

Nitrogen fixation measurements

The plants were collected in separate labelled paper bags and brought back to the laboratory, where the roots were gently washed under a stream of water and the root nodules separated from the plants and kept separately at 4°C before root nodule bacteria isolation. Plant shoots were separated from roots and oven dried at 60°C for 48 h and milled to a fine powder. The natural abundance rates of $^{15}N/^{14}N$, %N, and legumes and reference plants were determined by a Thermo Finnigan Delta Plus XP stable light isotope mass spectrometer (Fixon Instrument SPA, Strada Rivolla, Italy). About 2.0 mg of each pulverized sample was weighed in a tin capsule (Elementary Microanalysis LTD, Okehampton, UK) and run against two internal reference plant materials, namely *Nasturtium* sp. and *Vachellia* sp.

The isotopic composition of ^{15}N was measured as the difference in the number of atoms of ^{15}N to ^{14}N in atmospheric N_2 according to Junk & Svec (1958) and Mariotti (1983):

$$\delta^{15}N\ (‰) = \frac{(^{15}N/^{14}N)\ \text{sample} - (^{15}N/^{14}N)\text{standard}}{(^{15}N/^{14}N)\text{standard}} \times 1000$$

The percentage of N derived from the atmosphere (%Ndfa) was calculated according to Shearer & Kohl (1986) as follows:

$$\%Ndfa = \left[\frac{(\delta^{15}Nref) - \delta^{15}Nleg)}{(\delta^{15}Nref - B\ value)}\right] \times 100$$

where δ^{15}Nref is the mean ^{15}N natural abundance of a non-N_2-fixing reference plant, δ^{15}Nleg is the mean ^{15}N natural abundance of the legume (shoot), and the B value is the ^{15}N natural abundance of legume shoots that were totally dependent on biological N_2 fixation for their N nutrition.

The amount of N-fixed was calculated as proposed by Maskey et al. (2001):

$$\text{N-fixed} = (Ndfa/100) \times \text{legume shoot N}$$

After establishing normality, data on $\delta^{15}N$, %Ndfa, %N, and N-fixed were subjected to analysis of variance using STATISTICA version 13.1 (StatSoft Inc., 2016). Where there was statistical significance, means were separated using Fisher's LSD post hoc test.

Characterisation of bacteria

Bacteria that had been isolated (Vincent, 1970) from root nodules of groundnut and Bambara groundnut sampled from different farmers' fields in the Okavango delta and Tswapong area in Botswana were characterised. Bacterial physiological assays such as phosphate solubilisation and cellulase activities were carried out using specific growth media; for example, the Pikovskayas agar (Subba Rao, 1977) was used for phosphate solubilisation and cellulase activity detections (Teather & Wood, 1982).

Using bacteria as biofertiliser

Pennisetum glaucum (L.) R. Br. (pearl millet) was grown under sterile conditions in a greenhouse on three soils including a clayey, a loamy, and a sandy soil. A positive control using NPK fertiliser (2:3:2) and a negative control with

Table 1: Symbiotic traits of *Vigna subterranean* (L.) Verdc. and *Arachis hypogea* L. grown on farmers' fields in the Okavango delta and Tswapong areas of Botswana.

Agro-ecological zones	Farming area	Crop	$\delta^{15}N$ (‰)	%Ndfa	N-fixed ($kg.ha^{-1}$)	Number of plants/ha
Okavango	Xakao	*Vigna subterranean* (L.) Verdc.	1.8 ± 0.3a	50.3 ± 4.4c	0.3 ± 2.1c	230
Tswapong	Lekobeng	*Vigna subterranea* (L.) Verdc.	−1.2 ± 0.2c	96.4 ± 2.7a	1.3 ± 0.1a	213
Tswapong	Lekobeng	*Arachis hypogea* L.	0.5 ± 0.3b	69.3 ± 4.1b	0.8 ± 0.2bc	188
Okavango	Xakao	*Arachis hypogea* L.	0.5 ± 0.3b	71.0 ± 4.5b	1.2 ± 0.2ab	195

neither fertiliser nor inoculation were also included. Treatments were replicated four times. All the soils were sterilised in an autoclave to kill all microorganisms before commencement of experiments. Plants were harvested 45 days after planting by uprooting them with intact roots. They were oven dried at 60°C for 48 hours and they were weighed on a balance to obtain biomass.

Assessment of pest incidence in sorghum-legume intercropping

A field study to evaluate the effect of intercropping sorghum with legumes on damage caused by stemborer to sorghum was conducted in the 2015/2016 cropping season at Botswana University of Agriculture and Natural Resources in Sebele, Gaborone. Sorghum (*Sorghum bicolar* (L) Moench) was intercropped in an alternate fashion using a ratio of 1 row of sorghum to 2 rows of legume crop. There were four different legumes namely cowpea (*Vigna unguiculata* (L) Walp.), groundnut (*Arachis hypogea* L.), Bambara groundnut (*Vigna subterranea* (L.) Verdc.) and chickpea (*Cicer arietinum* L). The experiment was laid out in randomized complete block design, with four replications making a total to 20 experimental units. The individual plots were 5 m long with spacing between the rows of 0.75 m and between plants 0.30 m. The spacing between each block was 1 m and plots were labeled using pegs. Data on number of larvae per plant, number of stem tunnels, stem tunneling length and grain yield were collected. Suitability of sorghum plants grown under intercropping and monocrop was tested by measuring the content of N in plants. Data on stemborer damage, yield and nitrogen content were analyzed using mixed model and generalized linear model procedures (PROC MIXED and PROC GLM) (SAS Institute, 2008). All means of the data stated above were separated using Fisher's protected LSD test (significance level: $p \leq 0.05$). The relationship between yield and stemborer damage was tested using regression analysis. Yield loss was calculated as (1 – yield as proportion of the maximum yield) * 100 (Catangul et al., 2009). Maximum yield obtained from sorghum groundnut intercrop was used in the calculation of yield losses of different crop combinations. The relationship between nitrogen content (N) and stemborer damage on sorghum was determined using multiple regression analysis, with N as predictor variable and deadhearts, foliar damage, length of tunneling, number of tunnels and number of moth exit holes and number of larvae per plants as dependent variables. The best-fit models were selected based on stepwise procedures and the best subsets regression in Minitab® Release 17 (Minitab Inc., 2017)

Results

Nitrogen fixation and water use efficiency of indigenous herbaceous legumes

Table 1 shows levels of N_2 fixation of grain legumes at farm level in the Okavango Delta and Tswapong regions of Botswana. There were differences in levels of N_2 fixation between the two regions and between Bambara groundnut and groundnut. It is well accepted that levels of $\delta^{15}N$ less than 5‰ (Pule-Meulenberg & Dakora, 2009) indicate that plants are fixing N_2, thus, these crops formed a symbiotic N fixation with rhizobia, with the highest value of 1.8‰. Table 1 also shows that the dependence of the crops on symbiotic fixation was high, ranging between 50% and 96%. Interestingly, on hectare

Table 2: Sorghum yield and mean number of exit holes, number of tunnels, and length of tunnels caused by larvae of *C. partellus.*

Crop combination	Mean no. larvae	Mean no. exit holes	Mean no. tunnels	Mean length of tunnels	Yield (kg/ha)	§Yield loss (%)
Sorghum mono	12.50 ± 1.32a	14.75 ± 2.64a	7.10 ± 0.75a	0.50 ± 0.24a	33.86 ± 18.91b	87.86
Sorghum-cowpea	3.65 ± 0.74b	6.45 ± 1.90b	6.10 ± 0.61a	0.308 ± 0.54b	218.26 ± 46.10a	21.75
Sorghum-groundnut	4.60 ± 1.03b	7.35 ± 1.08b	4.45 ± 0.34b	0.43 ± 0.05a	278.93 ± 32.14a	0.00
Sorghum-Bambara	4.25 ± 0.65b	5.70 ± 1.08b	4.10 ± 0.37b	0.28 ± 0.37b	273.39 ± 77.37a	1.99
Sorghum-chickpea	4.35 ± 0.55b	7.05 ± 1.23b	4.05 ± 0.44b	0.31 ± 0.04b	234.82 ± 82.16a	15.81

§ No yield loss was calculated for groundnut because it was used as the maximum potential yield of sorghum gained by intercropping (see 'Materials and methods' for the formula used).

basis, actual amounts of N-fixed by these crops are very low, between 0.3 kg N/ha fixed by Bambara groundnut in Xakao and 1.3 kgN/ha by Bambara groundnut in Lekobeng, a farm area near Lecheng in the Tswapong region of Botswana. In Lekobeng, Bambara groundnut fixed more N_2 compared to groundnut, whereas the reverse was true in Xakao (Tab. 1).

Isolation and characterisation of bacteria as plant growth–promoting bacteria (PGPB)

In Botswana, after bacterial isolates were authenticated on their homologous hosts, they were all characterised for their ability to solubilise phosphate and for their cellulase activity. Figure 1 shows cultures that have been isolated from cowpea root nodules and assessed for plant growth promotion traits. Figure 1a is an example of a strain that tested positive for phosphatase solubility whereas Figure 1b was positive for cellulase activity. Both traits are detected by plate assay. Some of the strains were tested on millet in a greenhouse study where the effects of a cocktail of bacteria strains were compared to those of a positive control (NPK fertilizer application) and negative control (neither inoculum nor fertilizer application). Figure 2 shows that there were no significant differences in the number of leaves among the treatments for sandy and loamy soils. In a clayey soil, there were no differences in the number of pearl millet leaves between inoculated and NPK-fed plants, but the control plants exhibited a significantly lower number of leaves.

Pest reduction caused by intercropping with legumes

The study showed a significant increase in insect density of gramineous stemborer, *C. partellus,* on sorghum monocrop compared to the intercrops. Intercropping significantly reduced stemborer damage on sorghum compared to sorghum monocrop, where high levels occurred (Tab. 2). A significant reduction in the number of larvae per plant, number of stem tunnels, and stem tunneling length occurred with intercropping compared to monocropping. Grain yield increased significantly where sorghum was intercropped with grain legumes compared to monocrop (Tab. 2). There was a significant negative relationship between tunnel length, larval density, and yield, indicating that the increase in tunnelling caused by larval feeding significantly reduced yield (Fig. 3). Sorghum monocrop

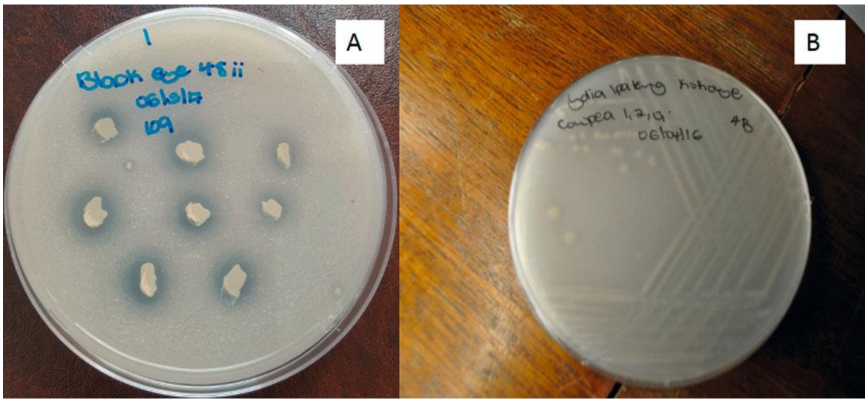

Figure 1: Plant growth promotion traits of bacteria isolated from cowpea root nodules on an agar plate/medium: (a) phosphate solubility (b) cellulase activity.

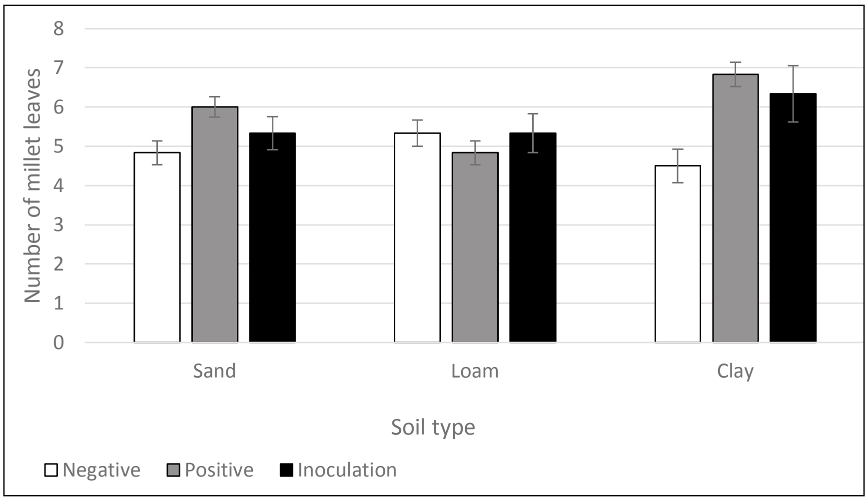

Figure 2: Interactive effect of inoculation and soil type on the number of millet leaves (mean) under greenhouse conditions. The error bars represent standard error (SE).

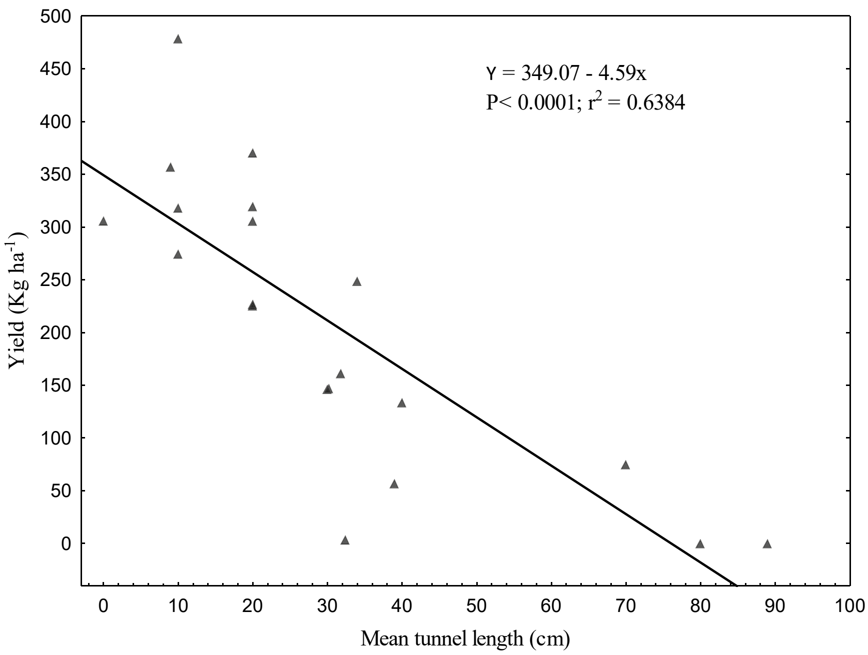

Figure 3: Relationship between sorghum grain yield and mean tunnel length caused by stemborer damage. Yield data were pooled from both mono- and intercropping treatments.

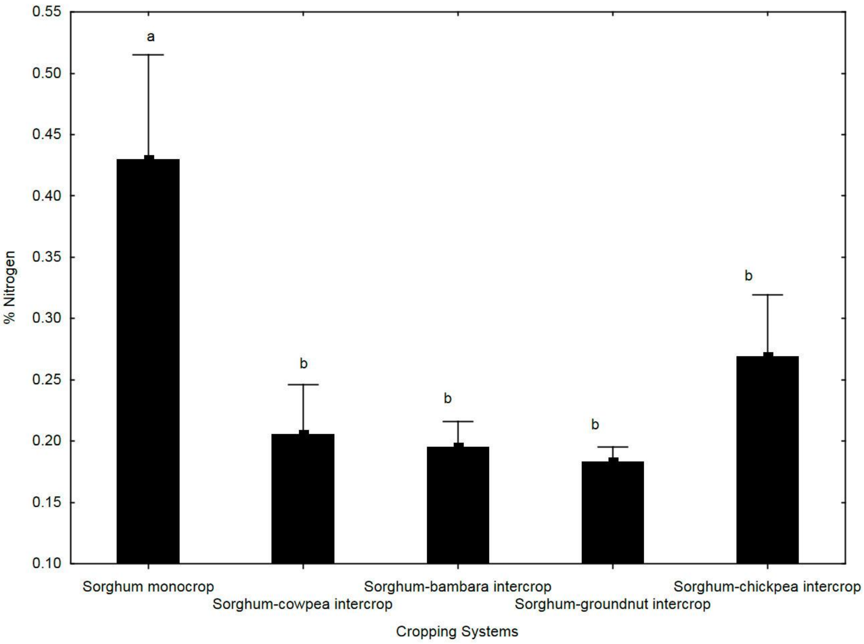

Figure 4: Nutrient composition based on percentage nitrogen content of sorghum plants under intercropping and monocropping, based on means. Letters associated with treatment indicate that a significance occurred (p ≤ 0.05). The error bars represent standard error (SE).

had the highest yield loss of 87%, significantly higher than in sorghum-legume intercrops.

The percentage of nitrogen content of sorghum plants after physiological maturity was significantly different between crop combinations ($F_{4,52} = 10.27$; $p < 0.0001$) (Fig. 4). The highest nutrient composition was obtained from sorghum monocrop. A significant relationship was observed between the percentage of nitrogen in sorghum and damage by *C. partellus* (number of dead hearts, number of live larvae, number of moth exit holes, and tunnel length) (Tab. 3).

Discussion

Farmers in semi-arid to arid areas such as in Botswana are challenged with less rainfall, declining soil fertility, and cultivation of more marginal land. With the advent of climate change, as predicted by climate change models (Archer et al., 2018), these areas are most likely to receive even less rainfall and experience higher temperatures, worsening the current situation. These areas are characterised by low yields, which make it imperative to develop more sustainable cropping systems. In Botswana, small-scale arable farmers are among the poorest in society. It is important that they have at their disposal appropriate and inexpensive technologies for increasing their crop yields without polluting the environment.

Inoculation of non-legumes

Cereals such as sorghum and millet and pulses such as cowpea and Bambara groundnut dominate the cropping system because of their drought tolerance and the ability of pulses to replenish soil N through symbiotic fixation. Apart from fixing nitrogen biologically, legumes are known to reduce soil erosion (Giller & Cadisch, 1995) and suppress weeds (Exner & Cruse, 1993). Up to 10% of the fixed N can directly benefit a cereal intercrop, and the rest the subsequent one (Dakora & Keya, 1997). In this study, positive results of inoculating non-legumes with root nodule bacteria were obtained. Inorganic fertilisers have been implicated in polluting the environment, especially when used injudiciously. Thus, other reasons to seek alternative ways of improving soil fertility include the fact that nitrogen fertilisers pollute groundwater and increase atmospheric nitric oxide (N_2O), a potent greenhouse gas. Alternative “green” fertilisers are therefore needed to mitigate negative effects of climate change. Inoculating cereals with biofertilisers is a step in the right direction. In this study, although inoculated plants did not perform to the level of NPK-fed plants, there was an advantage compared to control plants when grown on sand and clay. More studies are needed to test different types of bacteria on various cereals under greenhouse and field conditions.

Intercropping

The results from the intercropping study showed significantly higher *C. partellus* damage in the sorghum monocrop than in the sorghum-legume intercrop. Studies in tropical and temperate zones reported decreased pest densities in diversified cropping systems (Kruess & Tscharntke, 2000). Gahukar (1989) showed that females oviposited eggs on legume crops in the intercropped system and the hatched larvae failed to reach the sorghum plants. This may account for the reduced number of larvae and tunnelling on sorghum in the intercrops in the current study. With alternate row arrangements of host and non-host plants used in our study, the ovipositing female and dispersing larvae

Table 3: Relationship between host quality (%N) and various sorghum damage by *C. partellus.* The independent variable (predictor) was nitrogen content while the stemborer damages were dependent variables (data were pooled across intercrop combinations).

Stemborer damage	Intercept ± SE	Slope ± SE	r^2	*P*
% whorl damage	3.71 ± 3.98	0.470 ± 0.51	0.22	0.421
No. dead hearts	7.69 ± 1.26	0.96 ± 0.16	0.93	0.009
No. live larvae	29.32 ± 3.54	0.98 ± 0.12	0.94	0.004
No. moth exit holes	29.29 ± 2.58	0.98 ± 0.087	0.97	0.001
No. stem tunnels	9.21 ± 3.50	0.84 ± 0.32	0.70	0.078
Tunnel length	0.67 ± 0.22	0.87 ± 0.28	0.76	0.050

reportedly move easily within rather than between rows, explaining the low density of larvae on sorghum legume intercrop (Chabi-Olaye et al., 2005). The low densities of stemborer larvae on sorghum legume intercrop support the 'disruptive crop hypothesis' in which a second non-host plant species is suggested to affect the ability of the pest to find its proper host plant species through reduced chemical and visual cues and stimuli (Finch & Collier, 2000).

The lower larval densities in the intercropping system may additionally be explained by host plant quality. A study by Baidoo (2004) found that a higher nitrogen content of the stem of maize varieties resulted in a more severe stemborer infestation on these varieties. These results support our findings showing that plants with the highest percentage of nitrogen suffer great damage from the stemborer larvae (Fig. 4). Sorghum monocrop plants had the highest percentage of N and sustained the highest damage levels compared to sorghum-legume intercrops. Elevated nitrogen levels have been found to increase both the survival and the fecundity of stemborers, *Sesamia calamistis* (Setamou et al., 1995).

A significant increase in nutrient content in monocrop sorghum compared to intercrops agree with the host plant quality hypothesis, which states that intercropping negatively affects the host quality and the chemical suitability of the plants for herbivores when compared to the monocultures (Bach, 1981; van Lenteren, 1998). Yield in our study was negatively correlated with stem tunnelling by stemborer, which is known to injure the meristematic tissues of the plant, leading to a reduction in the yield (Bosque-Pérez & Mareck, 1991). In Africa, yield reduction by stemborer feeding and tunnelling can fall between 10% and 100%, depending on the season and status of the plant (Ndemah & Schulthess, 2002). In the current study, yield loss associated with sorghum monocrop was 87.9%, falling within the range reported by van den Berg (2009). Research by (Chabi-Olaye et al., 2005) showed that 3–8 times more stem tunnelling was recorded in maize monocrop, with high stemborer larval densities and yield loss (1.8–3.0 times greater), than in the intercropped system. In our study, larval densities were up to 3 times more in the sorghum monocrop than in the intercrops.

Results from this study have shown that bacteria isolated from the root nodules of legumes have potential as biofertilisers, as shown by positive growth of sorghum and pearl millet when inoculated with bacterial cocktails. Bacterial assays for phosphate solubilisation and cellulase activity confirmed mechanisms of plant growth promotion. Furthermore, intercropping of sorghum with legumes led to a reduction in stemborer infestation on the sorghum, leading to higher yields. In conclusion, our data reveal the potential for the use of microorganisms in sustainable cropping systems as biofertilisers. However, further studies are required to test the bacteria under various scenarios in the field. The data on intercropping that show reduced stemborer infestation under intercropping are directly applicable and should be packaged for use by smallholder farmers, as stemborers are important pests of sorghum in Botswana.

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References

Archer, E., Engelbrecht, F., Hänsler, A., Landman, W., Tadross, M. & Helmschrot, J. (2018) Seasonal prediction and regional climate projections for southern Africa. This volume.

Bach, C.E. (1981). Host plant growth form and diversity: effects on abundance and feeding preference of a specialist herbivore, *Acalymma vittata* (Coleoptera: Chrysomelidae). *Oecologica*, **50**, 370–375.

Baidoo, P.K. (2004) The role of silica and nitrogen in resistance of maize to stemborer attack. *Journal of Science and Technology*, **24**, 1–4.

Bosque Pérez, N.A. & Mareck, J.H. (1991) Effect of the stemborer *Eldana saccharina* (Lepidoptera: Pyralidae) on the yield of maize. *Bulletin of Entomological Research*, **81**, 243–247.

Catangul, M., Beckendorf, E.A. & Riedell, W. E. (2009) Soybean aphid population dynamics, soybean yield loss, and development of stage-specific Economic Injury Level. *Agronomy Journal*, **101**, 1080–1092.

Chabi-Olaye, A., Nolte, C., Schulthess, F. & Borgemeister, C. (2005) Abundance, dispersion and parasitism of the noctuid stemborer *Busseola fusca* (Fuller) in mono- and intercropped maize in the humid forest zone of southern Cameroon. *Bulletin of Entomological Research*, **95**, 169–177.

Dakora, F.D. & Keya, S.O. (1997) Contribution of legume nitrogen fixation to sustainable agriculture in Sub-Saharan Africa. *Soil Biology and Biochemistry*, **29**, 809–817.

Exner, D.N. & Cruse, R.M. (1993) Interseed forage legume potential as winter ground cover, nitrogen source and competitor. *Journal of Production Agriculture*, **6**, 226–231.

Finch, S. & Collier, R.H. (2000) Host-plant selection by insects — a theory based on 'appropriate/inappropriate landings' by pest insects of cruciferous plants. *Entomologia Experimentalis et Applicata*, **96**, 91–102.

Gahukar, R.T. (1989) Insect pests of millet and their management: a review. *International Journal of Pest Management*, 35, 382–391.

Garcia-Pausas, J. & Paterson, E. (2011) Microbial community abundance and structure are determinants of soil organic matter mineralisation in the presence of labile carbon. *Soil Biology and Biochemistry*, **43**, 1705–1713.

Giller, K.E. & Cadisch, G. (1995) Future benefits from biological nitrogen-fixation — an ecological approach to agriculture. *Plant and Soil*, **174**, 255–277.

Glick, B.R. (2012) Plant growth–promoting bacteria: mechanisms and applications. *Scientifica*, 2012, Article 963401.

Gregory, A.S., Watts, C.W., Griffiths, B.S., Hallett, P.D., Kuan, H.L. & Whitmore, A.P. (2009) The effect of long-term soil management on the physical and biological resilience of a range of arable and grassland soils in England. *Geoderma*, **153**, 172–185.

Hulme, M. (1996) *Climate change and southern Africa: an exploration of some potential impacts and implications for the SADC region*. Climatic Research Unit, University of East Anglia, Norwich, UK.

Junk, G., Svec, H.J. (1958) The absolute abundance of the nitrogen isotopes in the atmosphere and compressed gas from various sources. Geochim Cosmochim Acta 14:234–243

Kfir, R., Overholt, W.A., Khan, Z.R. & Polaszek, A. (2002) Biology and management of economically important Lepidopteran cereal stemborers in Africa. *Annual Review of Entomology,* **47**, 701–731.

Khan, Z.R., James, D.G., Midega, C.A.O. & Pickett, J.A. (2008) Chemical ecology and conservation biological control. *Biological Control*, **45**, 210–224.

Kruess, A. & Tscharntke, T. (2000) Species richness and parasitism in a fragmented landscape: experiments and field studies with insects on *Vicia sepium*. *Oecologia*, **122**, 129–137.

Mace, E.S., Tai, S., Gilding, E.K. et al. (2013) Whole-genome sequencing reveals untapped genetic potential in Africa's indigenous cereal crop sorghum. *Nature Communications*, **4**, 2320.

Mariotti, A. (1983) Atmospheric nitrogen is a reliable standard for natural ^{15}N abundance measurements. *Nature* 303:685–687.

Maskey, S.L., Bhattarai, S., Peoples, M.B., Herridge, D.F. (2001) On-farm measurements of nitrogen fixation by winter and summer

legumes in the Hill and Terai regions of Nepal. Field Crop Research, 70:209–221.
Minitab Inc. (2017) Minitab 17 statistical software. Minitab Inc., State College, PA.
Mosinkie, K.T. & Obopile, M. (2001) Management practices and farmers' perception on insect pests in Botswana. *Proceedings of the final workshop of the Southern Africa Stemborer Management Programme, Pietermaritzburg, 2–5 July 2001* (ed. by J. van den Berg and V.M. Uys), pp.
Ndemah, R. & Schulthess, F. (2002) Yield of maize in relation to natural field infestations and damage by lepidopterous borers in the forest and forest/savanna transition zones of Cameroon. *Insect Science and Its Application*, **22**, 183–193.
Obopile, M. & Mosinkie, K.T. (2001) A survey of cereal stemborers and their natural enemies in Botswana. *Proceedings of the final workshop of the Southern Africa Stemborer Management Programme, Pietermaritzburg, 2–5 July 2001* (ed. by J. van den Berg and V.M. Uys), pp.
Pule-Meulenberg, F. & Dakora, F.D. (2009) Assessing the symbiotic dependency of grain and tree legumes on N_2 fixation for their N nutrition in five agro-ecological zones of Botswana. *Symbiosis*, **48**, 68–77.
Roome, R.E. (1970) *Report of the entomological team: In: Annual report of Research Section 1968–1969.* Government Printer, Gaborone, Botswana.
SAS Institute. 2008. SAS Users Guide: Statistics. SAS Institute. Cary, North Carolina
Schwyn, B. & Neilands, J.B. (1987) Universal chemical assay for the detection and determination of siderophores. *Analytical Biochemistry*, **160**, 47–56.
Sétamou, M., Schulthess, F., Bosque-Pérez, N.A. & Thomas-Odjo, A. (1995) The effect of stem borers on maize subjected to different nitrogen treatments. *Entomologia Experimentalis et Applicata,* **77**, 205–210.
Shearer, G., Kohl, D.H. (1986) N_2-fixation in field settings: estimations based on natural ^{15}N abundance. *Functional Plant Biology*, 13:699–756
Statistics Botswana (2016). Annual agricultural statistics. Botswana Government Printers, Gaborone.
StatSoft Inc., (2016 Statistical. Data Analysis. Software. System. 13.1. <http://www.statsoft.com/>
Subba Rao, N.S. (1977) *Soil microorganisms and plant growth*. Oxford and IBH Publishing Co., New Delhi
Teather, R.M. & Wood, P.J. (1982) Use of Congo red-polysaccharide interactions in enumeration and characterization of cellulolytic bacteria from the bovine rumen. *Applied and Environmental Microbiology*, 43, 777–780.
Teetes, G.L. (1985) Insect-resistant sorghum in pest management. *Insect Science and Its Application*, **6**, 443–451.
Van den Berg, J. (1994) *Integrated pest management of stem borers on grain sorghum*. PhD thesis, University of Orange Free State, Bloemfontein, South Africa.
van den Berg, J. (2009) Case study: vetiver grass as component of integrated pest management systems. http://www.vetiver.org/ETH_WORKSHOP_09/ETH_A3a.pdf
Van Lenteren, J.C. (1998) Ecosystem services to biological control of pests: why are they ignored? *Proceedings, of the Netherlands Entomology Society meeting* pp. 409–413.
Vincent, J.M. (1970) *A manual for the practical study of root-nodule bacteria*. IBP handbook no. 15. Blackwell, Oxford, UK.

References [CrossRef]

Archer, E., Engelbrecht, F., Hänsler, A., Landman, W., Tadross, M. & Helmschrot, J. (2018) Seasonal prediction and regional climate projections for southern Africa. This volume. CrossRef

Bach, C.E. (1981). Host plant growth form and diversity: effects on abundance and feeding preference of a specialist herbivore, *Acalymma vittata* (Coleoptera: Chrysomelidae). *Oecologica*, **50**, 370–375. CrossRef

Baidoo, P.K. (2004) The role of silica and nitrogen in resistance of maize to stemborer attack. *Journal of Science and Technology*, **24**, 1–4.

Bosque Pérez, N.A. & Mareck, J.H. (1991) Effect of the stemborer *Eldana saccharina* (Lepidoptera: Pyralidae) on the yield of maize. *Bulletin of Entomological Research*, **81**, 243–247. CrossRef

Catangul, M., Beckendorf, E.A. & Riedell, W. E. (2009) Soybean aphid population dynamics, soybean yield loss, and development of stage-specific Economic Injury Level. *Agronomy Journal*, **101**, 1080–1092. CrossRef

Chabi-Olaye, A., Nolte, C., Schulthess, F. & Borgemeister, C. (2005) Abundance, dispersion and parasitism of the noctuid stemborer *Busseola fusca* (Fuller) in mono- and intercropped maize in the humid forest zone of southern Cameroon. *Bulletin of Entomological Research*, **95**, 169–177. CrossRef

Dakora, F.D. & Keya, S.O. (1997) Contribution of legume nitrogen fixation to sustainable agriculture in Sub-Saharan Africa. *Soil Biology and Biochemistry*, **29**, 809–817. CrossRef

Exner, D.N. & Cruse, R.M. (1993) Interseed forage legume potential as winter ground cover, nitrogen source and competitor. *Journal of Production Agriculture*, **6**, 226–231. CrossRef

Finch, S. & Collier, R.H. (2000) Host-plant selection by insects — a theory based on 'appropriate/inappropriate landings' by pest insects of cruciferous plants. *Entomologia Experimentalis et Applicata*, **96**, 91–102. CrossRef

Gahukar, R.T. (1989) Insect pests of millet and their management: a review. *International Journal of Pest Management*, **35**, 382–391. CrossRef

Garcia-Pausas, J. & Paterson, E. (2011) Microbial community abundance and structure are determinants of soil organic matter mineralisation in the presence of labile carbon. *Soil Biology and Biochemistry*, **43**, 1705–1713. CrossRef

Giller, K.E. & Cadisch, G. (1995) Future benefits from biological nitrogen-fixation — an ecological approach to agriculture. *Plant and Soil*, **174**, 255–277. CrossRef

Glick, B.R. (2012) Plant growth–promoting bacteria: mechanisms and applications. *Scientifica*, **2012**, Article 963401. CrossRef

Gregory, A.S., Watts, C.W., Griffiths, B.S., Hallett, P.D., Kuan, H.L. & Whitmore, A.P. (2009) The effect of long-term soil management on the physical and biological resilience of a range of arable and grassland soils in England. *Geoderma*, **153**, 172–185. CrossRef

Hulme, M. (1996) *Climate change and southern Africa: an exploration of some potential impacts and implications for the SADC region*. Climatic Research Unit, University of East Anglia, Norwich, UK.

Junk G, Svec HJ (1958). The absolute abundance of the nitrogen isotopes in the atmosphere and compressed gas from various sources. Geochim Cosmochim Acta 14:234‑243. CrossRef

Kfir, R., Overholt, W.A., Khan, Z.R. & Polaszek, A. (2002) Biology and management of economically important Lepidopteran cereal stemborers in Africa. *Annual Review of Entomology*, **47**, 701–731. CrossRef

Khan, Z.R., James, D.G., Midega, C.A.O. & Pickett, J.A. (2008) Chemical ecology and conservation biological control. *Biological Control*, **45**, 210–224. CrossRef

Kruess, A. & Tscharntke, T. (2000) Species richness and parasitism in a fragmented landscape: experiments and field studies with insects on *Vicia sepium*. *Oecologia*, **122**, 129–137. CrossRef

Mace, E.S., Tai, S., Gilding, E.K. et al. (2013) Whole-genome sequencing reveals untapped genetic potential in Africa's indigenous cereal crop sorghum. *Nature Communications*, **4**, 2320. CrossRef

Mariotti A (1983) Atmospheric nitrogen is a reliable standard for natural ^{15}N abundance measurements. *Nature* 303:685‑687. CrossRef

Maskey SL, Bhattarai S, Peoples MB, Herridge DF (2001) On-farm measurements of nitrogen fixation by winter and summer legumes in the Hill and Terai regions of Nepal. Field Crop Research, 70:209‑221. CrossRef

Minitab Inc. (2017) Minitab 17 statistical software. Minitab Inc., State College, PA.

Mosinkie, K.T. & Obopile, M. (2001) Management practices and farmers' perception on insect pests in Botswana. *Proceedings of the final workshop of the Southern Africa Stemborer Management Programme, Pietermaritzburg, 2–5 July 2001* (ed. by J. van den Berg and V.M. Uys).

Ndemah, R., & Schulthess, F. (2002) Yield of maize in relation to natural field infestations and damage by lepidopterous borers in the forest and forest/savanna transition zones of Cameroon. *Insect Science and Its Application*, **22**, 183–193.

Obopile, M. & Mosinkie, K.T. (2001) A survey of cereal stemborers and their natural enemies in Botswana. *Proceedings of the final workshop of the Southern Africa Stemborer Management Programme, Pietermaritzburg, 2–5 July 2001* (ed. by J. van den Berg and V.M. Uys).

Pule-Meulenberg, F. & Dakora, F.D. (2009) Assessing the symbiotic dependency of grain and tree legumes on N_2 fixation for their N nutrition in five agro-ecological zones of Botswana. *Symbiosis*, **48**, 68–77. CrossRef

Roome, R.E. (1970) *Report of the entomological team: In: Annual report of Research Section 1968–1969*. Government Printer, Gaborone, Botswana.

SAS Institute. 2008. SAS Users Guide: Statistics. SAS Institute. Cary, North Carolina

Schwyn, B. & Neilands, J.B. (1987) Universal chemical assay for the detection and determination of siderophores. *Analytical Biochemistry*, **160**, 47–56. CrossRef

Sétamou, M., Schulthess, F., Bosque-Pérez, N.A., & Thomas-Odjo, A. (1995) The effect of stem borers on maize subjected to different nitrogen treatments. *Entomologia Experimentalis et Applicata*, **77**, 205–210. CrossRef

Shearer G, Kohl DH (1986) N_2-fixation in field settings: estimations based on natural ^{15}N abundance. *Functional Plant Biology*, 13:699‑756. CrossRef

Statistics Botswana (2016). Annual agricultural statistics. Botswana Government Printers, Gaborone.

StatSoft Inc., (2016 Statistical. Data Analysis. Software. System. 13.1. <http://www.statsoft.com/>

Subba Rao, N.S. (1977) *Soil microorganisms and plant growth*. Oxford and IBH Publishing Co., New Delhi

Teather, R.M. & Wood, P.J. (1982) Use of Congo red-polysaccharide interactions in enumeration and characterization of cellulolytic bacteria from the bovine rumen. *Applied and Environmental Microbiology*, **43**, 777–780.

Teetes, G.L. (1985) Insect-resistant sorghum in pest management. *Insect Science and Its Application*, **6**, 443–451. CrossRef

Van den Berg, J. (1994) *Integrated pest management of stem borers on grain sorghum*. PhD thesis, University of Orange Free State, Bloemfontein, South Africa.

van den Berg, J. (2009) Case study: vetiver grass as component of integrated pest management systems. http://www.vetiver.org/ETH_WORKSHOP_09/ETH_A3a.pdf

Van Lenteren, J.C. (1998) Ecosystem services to biological control of pests: why are they ignored? *Proceedings, of the Netherlands Entomology Society meeting* pp. 409–413.

Vincent, J.M. (1970) *A manual for the practical study of root-nodule bacteria*. IBP handbook no. 15. Blackwell, Oxford, UK.

Food security

Germplasm evaluation for climate adaptation and drought tolerance: The cases of local varieties of maize in Zambia and cowpea in Botswana

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Abstract: Water shortages as a result of changes in rainfall patterns and increases in temperatures are associated with climate change. Rising temperatures and evaporation rates exacerbate water scarcity problems primarily affecting dry-land crop production systems in southern Africa. Thus, the search for drought-tolerant crop varieties becomes necessary to mitigate climate change and to achieve food security in the region. Fifty maize germplasm accessions obtained from the Zambian gene bank were characterized at Mount Makulu Research Station in Zambia to identify suitable varieties for on-farm evaluation. In that regard, data was collected on days to 50% tasselling, days to silking, plant height, ear height, number of leaves above leaf ear, tillering index, tassel type, number of kernel rows, kernel type, and kernel colour. Furthermore, we carried out on-farm participatory evaluation of 20 local varieties of maize at two representative sites. Farmers selected six crop varieties on the basis of their early maturity, high yielding ability, drought tolerance, and tolerance to field pests and diseases. The selected maize varieties are suitable for large-scale production or variety development for the targeted sites or areas with similar agro-ecological conditions.

In Botswana, greenhouse and field studies were conducted to characterise 20 cowpea genotypes based on different drought tolerance indices. Results showed that stress tolerance index (STI) and drought resistance index (DI) were the most suitable indices for selecting cowpea genotypes for drought tolerance. Six cowpea collections were tested in a field study at Hukuntsi, situated in the Kalahari Desert, in 2014-15. Analysis of variance and regression analysis showed that three accessions [BCA001 (Blackeye), BCA009 (Mahutohuto), BCA016 (Speckled brown] were promising drought-tolerant varieties displaying a higher plant drought survival (PDS%) rate under field conditions. Significant correlations were detected between PDS% and STI, indicating the usefulness of the two parameters in selecting drought-tolerant cowpea genotypes. The two selected cowpea genotypes are recommended for cultivar development or production under drought-prone and rain-fed farming systems in southern Africa.

Resumo: A escassez de água, resultante das alterações nos padrões de precipitação e do aumento da temperatura, está associada às alterações climáticas. O aumento da temperatura e das taxas de evaporação exacerbam os problemas de escassez de água, principalmente nos sistemas de produção de culturas de sequeiro no Sul de África. Assim, a procura de variedades de culturas tolerantes à seca torna-se necessária para mitigar as alterações climáticas e alcançar segurança alimentar na região. Cinquenta acessos de germoplasma de milho, obtidos do banco de genes Zambiano, foram caracterizados na Estação de Investigação de Mount Makulu na Zâmbia, de modo a identificar variedades adequadas para avaliação em quintas. Nesse contexto, foram recolhidos dados sobre o número de dias que demora a crescer 50% do pendão, o número de dias que demora a crescer as estigmas, a altura da planta, a altura da espiga, o número de folhas acima da folha da espiga, o índice de perfilhamento, o tipo de pendão, o número de filas de grãos e o tipo e cor do grão. Para além disso, realizámos avaliações participativas no terreno de 20 variedades locais de milho em dois locais representativos. Os agricultores seleccionaram seis

variedades de culturas com base na sua maturidade precoce, alta capacidade de rendimento, tolerância à seca e tolerância a pragas e doenças no campo. As variedades de milho seleccionadas são adequadas para a produção em grande escala ou desenvolvimento de variedades para locais específicos ou áreas com condiçoes agro-ecológicas semelhantes.
No Botswana, foram realizados estudos de campo e em estufas para caracterizar 20 genótipos de feijão-frade com base em diferentes indíces de tolerância à seca. Os resultados mostraram que o índice de tolerância ao stress (STI) e o índice de resistência à seca (DI) foram os mais adequados para a selecção de feijão-frade com tolerância à seca. Seis colecções de feijão-frade foram testadas num estudo de campo em Hukuntsi, situado no Deserto do Kalahari, em 2014/15. A análise da variância e a análise da regressão mostraram que três acessos [BCA001 (*Blackeye*), BCA009 (*Mahutohuto*), BCA016 (*Speckled brown*] eram variedades tolerantes à seca promissoras, apresentando uma maior taxa de sobrevivência à seca (PSD%) em condições de campo. Correlações significativas foram detectadas entre PDS% e STI, indicando a utilidade dos dois parâmetros na selecção de genótipos de feijão-frade tolerantes à seca. Os dois genótipos de feijão-frade seleccionados são recomendados para o desenvolvimento ou produção de culturas em sistemas agrícolas de sequeiro, ou susceptíveis à seca, no Sul de África.

Introduction

Climate change in many parts of the developing world brings about water shortages as a result of changes in rainfall patterns and increases in temperatures. Rising temperatures and evaporation rates may exacerbate water scarcity problems affecting dry-land crop production systems as a result of drought. Drought, also known as water deficit, can result from the presence of insufficient moisture for a plant to grow adequately and complete its life cycle. Insufficient moisture can be the consequence of water shortage, coarsely textured soils that retain little water in the root zone, or drying winds. Both droughts and heat waves are predicted to occur more frequently and become more problematic in many areas (Lindner et al., 2010)

Southern Africa is described as a hotspot of climate change, experiencing increased frequency of heat and drought stress (Tubiello et al., 2007; Stringer et al., 2009; Archer et al., 2018). The situation will be worsened by soil erosion and degradation, as well as a decline in the availability of water. Evidence suggests that in this region, climate change may decrease the yields of many crops by shortening the growing season and amplifying water stress, among other factors. The key vulnerable sectors identified by the Intergovernmental Panel on Climate Change (IPCC, 2007b) include agriculture, food, and water. This part of Sub-Saharan Africa is expected to suffer the most not only in terms of reduced agricultural productivity and increased water insecurity, but also through increased exposure to extreme climatic events. The region's vulnerability to climate change is exacerbated by a number of non-climatic factors, including low levels of development and low adaptive capacity. To adapt crop germplasm to climate change scientists look for genetic resources with traits supporting drought adaptation. The ability to develop new varieties depends on their access to genetic resources with traits of economic interest, as well as their technical ability to incorporate these traits into breeding materials and subsequently into commercial varieties.

Crops such as maize, sorghum, pearl millets, cassava, yam, banana, coffee (Ramirez-Villegas & Thornton, 2015) and various legumes (Foyer et al., 2016) are critical for food security in southern Africa. The importance of legumes such as cowpea for food security and sustainable cropping systems has been extensively documented (Sidique et al., 2012). Maize is the most important source of dietary protein and the second most important source of calories in southern Africa. In Zambia, local maize populations have been cultivated for a long time and therefore have been subjected to natural and human selection in different agro-ecological regions and production environments. Such successful adaptation to local growing conditions explains why most traditional farmers prefer local and traditional varieties, which are usually differentiated by a number of specific morphological and agronomic traits. Recently, however, it has become apparent that diversity of local germplasm is declining as a result of the influence of national policy on agriculture, promoting improved varieties (Langyintuo & Mungoma, 2008).

In Botswana, cowpea production is practiced in rain-fed agricultural systems. The latest Agricultural Census Report (CSO, 2013) indicated that cowpea is among the most cultivated crops after maize and sorghum, contributing 10% to the total agricultural production. However, a recent crop census indicated a significant drop in production and productivity of cowpea agriculture, attributed to low and erratic rainfalls (MoA, 2010). Production is more dominant in the eastern part of the country and there are efforts by authorities to promote cowpea production in the Kalahari and Ghanzi Districts (Kalahari Desert), where conditions are generally unfavourable for crop production. Cowpea is a relatively drought-tolerant crop, has adapted to high temperatures and other stresses such as low soil fertility, and can cope with a wide range of soil pH, making it a crop of interest for the changing environmental conditions associated with climate change. Traits to be considered as potential selection targets for improving yield under water-limited conditions must be genetically correlated with yield and should have a greater heritability. Measurements of target trait such as yield should be rapid, accurate, and inexpensive (Tuberosa, 2012).

In light of impending climate change in the SASSCAL region, maize and cowpea varieties grown by farmers may not withstand the projected stresses, with resultant losses in productivity and potentially negative consequences for food security. One strategy for responding to this situation is to identify drought-adapted germplasm from farmers, gene banks, and research organizations that can withstand similar climatic conditions elsewhere. Therefore, two case studies were undertaken with the following objectives: (i) to evaluate and select maize germplasm obtained from the national gene bank in Zambia; (ii) to assess the effectiveness of drought tolerance indices as indicators for drought tolerance in cowpea; and (iii) to identify drought-tolerant cowpea genotypes from a large population growing under field conditions in Botswana. The selected local varieties can be useful genetic resources for direct production or may have their traits incorporated via plant breeding programs.

Case Study I. Agro-morphological evaluation of maize germplasm in Zambia

Field experiments

Two field studies were undertaken to identify and assess maize germplasm accessions held in the gene bank at Mount Makulu Research Station. The first field study was conducted on station to assess the agro-morphological diversity of the germplasm accessions and identify accessions with inherent characteristics such as early maturing that enable the crop to survive drought occurring later in the season. The second study involved participatory evaluation of 20 varieties grown in farmers' fields in the Rufunsa and Shiwuyunji districts.

Plant materials

A total of 50 maize germplasm accessions originally collected from Rufunsa, Shiwuyunji, and other regions with similar agro-ecological conditions and conserved in the Zambian national gene bank were involved in the on-station field trial.

Study sites

Agro-morphological characterisation of maize germplasm accessions in a single season involved one experimental site at Mount Makulu Research Station (15°33′S; 28°11′E). Participatory evaluation and selection of maize varieties involving farmers was undertaken on farmers' fields at sites in Rufunsa (15°04′S; 29°40′E) and Shiwuyunji (15°23′21.2″S; 27°42′9.3″E) situated in the Lusaka and Central Provinces of Zambia.

Experimental design and agronomic management at the research station

The germplasm accessions were grown in a single plot without replication. The maize germplasm accessions were planted at interrow spacing of 90 cm and intrarow spacing of 30 cm, providing a spacing of 2 m between accessions.

Agro-morphological data at the vegetative and reproductive growth stages of the crop were recorded for 10 randomly selected plants for each accession according to the International Board for Plant Genetic Resources descriptor list for maize (IBPGR ROME, 1991). We measured the following morphological characteristics: days to tassel (DTT), days to silking (DTS), plant height (PH), ear height (EH), number of leaves (NLL), tillering index (TI), stem colour (SC), tassel type (TT), number of kernel rows (NKR), kernel type (KT), and kernel colour (KC). Qualitative data were scored as binary data (present/absent). The agro-morphological traits measured on the 50 germplasm accessions of maize were subjected to principal component analysis using NTSYSpc 2.21 (Rohlf, 1998).

Experimental design of field experiments and participatory evaluation

We carried out participatory selection of the maize varieties at two sites in Zambia using farmers' own criteria in order to enhance adoption of the selected varieties. A total of 20 out of the 50 local maize varieties were involved in participatory evaluation at each of the two study sites (Tab. 1). The maize varieties involved in the study met the criteria of suitability for the target sites involved.

The field experimental design used for on-farm evaluation of the maize varieties was randomised complete block design (RCBD) with three blocks or replicates. A total of three fields of different farmers were involved at each of the two sites and each field represented one replicate or experimental block. Each field held a total of 20 maize accessions. At each study site, we included maize accessions that had previously been collected in the area. The accessions were: ZMB8172, ZMB4429, ZMB4436, and ZMB8196 at Rufunsa and ZMB8160, ZMB5205, and ZMB6846 at Shiwuyunji. Maize accessions were planted in four rows, each 5 m long, at interrow spacing of 90 cm and intrarow spacing of 30 cm. The plot dimensions were 2.7 m x 5 m, and in order to

Table 1: Maize germplasm accessions used in the participatory evaluation; accessions were collected from Rufunsa, Shiwuyunji, other regions, and the National Gene Bank in Zambia.

Serial No.	Accession	Local name	Site of evaluation
1	ZMB5045	Chilala	Rufunsa
2	ZMB8262	Chilala	Rufunsa
3	ZMB8217	Kafwamba	Rufunsa
4	ZMB8214	Local	Rufunsa
5	ZMB4429	Kafwamba	Rufunsa
6	ZMB8154	Sesheke	Rufunsa
7	ZMB8174	Mboni ya sintu	Rufunsa
8	ZMB8215	Kangalingali	Rufunsa
9	ZMB4745	Chulu chitu	Rufunsa
10	ZMB8212	Chilala	Rufunsa
11	ZMB8172	Chilala	Rufunsa
12	ZMB8213	Chilala	Rufunsa
13	ZMB8216	Chilala	Rufunsa
14	ZMB8165	Akansalika	Rufunsa
15	ZMB6611	Chiyongoli	Rufunsa
16	ZMB7476	Kampala	Rufunsa
17	ZMB4436	Gankata	Rufunsa
18	ZMB8196	Kanjele	Rufunsa
19	ZMB8256	Kanjele	Rufunsa
20	ZMB6653	Yachisi	Rufunsa
21	ZMB7456	Kanjele	Shiwuyunji
22	ZMB5203	Gankanta	Shiwuyunji
23	ZMB6639	Kafwamba	Shiwuyunji
24	ZMB6866	Gankata	Shiwuyunji
25	ZMB5195	Gankata	Shiwuyunji
26	ZMB5194	Kafwamba	Shiwuyunji
27	ZMB8260	Kafwamba	Shiwuyunji
28	ZMB6614	Gankata	Shiwuyunji
29	ZMB6863	Gankata	Shiwuyunji
30	ZMB6628	Gankata	Shiwuyunji
31	ZMB5205	Gankata	Shiwuyunji
32	ZMB6623	Jereman	Shiwuyunji
33	ZMB4231	Kafwamba	Shiwuyunji
34	ZMB8259	Kafwamba	Shiwuyunji
35	ZMB6843	Kapyapya	Shiwuyunji
36	ZMB4445	Gankata	Shiwuyunji
37	ZMB8160	Gankata	Shiwuyunji
38	ZMB6846	Gankata	Shiwuyunji
39	ZMB6656	Kasenga	Shiwuyunji
40	ZMB6653	Kafumbushi	Shiwuyunji

allow sufficient space between varieties, the distance between adjacent plots was maintained at 2 m.

Process of participatory selection of maize varieties

When the maize crop growth stage was nearing physiological maturity, farmers were invited to evaluate the performance of the maize varieties (Fig. 1). Prior to field evaluation of the varieties, farmers selected their own criteria to be used in the assessment. The traits of importance to farmers that formed the basis for selecting maize varieties were early maturity, high yielding ability, drought tolerance, and tolerance to field pests and diseases. Farmers were then asked to walk through the trial field and record the plot(s) containing the maize varieties they liked most based on their set criteria. Note that early maturity was considered an important criterion by farmers at both sites for two main reasons. First, early maturing varieties allowed farmers to harvest their crop earlier in the season in consideration of changed rainfall patterns; additionally, the trait permits the crop to escape drought periods which occur after fertilization. Both factors help ensure early and quick provision of cash and food to farmers' households to alleviate hunger.

Figure 1: A group of farmers involved in participatory evaluation of maize germplasm accessions on farm at one of the three sites in Rufunsa District.

Table 2: Principal components (PC), eigenvalues, proportion, and cumulative variance attributed to the 10 traits of maize germplasm

PC	Variable	Eigenvalue	Percent	Cumulative
1	Days to 50% Tasseling (DTT)	2.46680897	24.6681	24.6681
2	Days to Silking (DTS)	1.89682003	18.9682	43.6363
3	Plant Height (PH)	1.26775672	12.6776	56.3139
4	Ear Height (EH)	1.16708705	11.6709	67.9847
5	Number of leaves above upper ear (NLUE)	1.10279524	11.028	79.0127
6	Tassel Type (TT)	0.82457977	8.2458	87.2585
7	Number of Kernel Rows (NKR)	0.64926709	6.4927	93.7511
8	Kernel Type (KT)	0.41567904	4.1568	97.9079
9	Kernel colour (KC)	0.17830817	1.7831	99.691
10	1000 Kernel weight (1000KW)	0.03089793	0.309	100

Results

Principal component analysis (PCA) yielded five significant principal components with significant Eigen value > 1.0: days to 50% tasseling (DTT), days to silking (DTS), plant height (PH), ear height (EH), and number of leaves above upper ear (NLUE), with each explaining 24.7%, 19.0%, 12.7%, 11.7%, and 11.0% of the total observed variation respectively (Tab. 2). Cumulatively, these five principal components explained a total of 79.1% of the observed variation.

The plot of the first two components of the PCA of the maize varieties and the 10 traits yielded a pattern in which traits days to tassel (DTT) and days to silking (DTS) enabled grouping of the following genotypes: ZMB8178, ZMB8244, ZMB7442, and ZMB7283 (Fig. 2). In a similar manner, ear height (EH), plant height (PH),

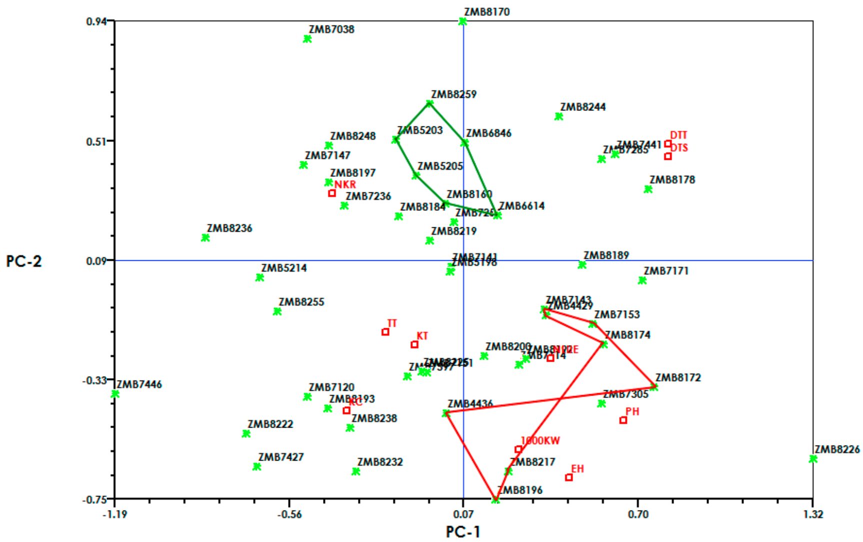

Figure 2: A two-dimensional plot of the 50 maize germplasm accessions and 11 traits studied. The traits used in the analysis were days to 50% tassel (DTT), days to silking (DTS), plant height (PH), ear height (EH), number of leaves (NLL), tillering index (TI), stem colour (SC), tassel type (TT), number of kernel rows (NKR), kernel type (KT), and kernel colour (KC). Principal Component 1 (PC1) explains 25% and PC2 explains 19% of the observed variation. Preferred maize varieties in Shiwuyunji and Rufunsa are in green and red boxes respectively.

thousand-kernel weight (1 000 KW), and number of leaves above upper ear (NLUE) allocated ZMB7305, ZMB8172, ZMB8217, ZMB8196, ZMB7235, ZMB7153, and ZMB7171 into one group. Similarity among tassel type (TT), kernel type (KT), and kernel colour (KC) enabled us to allocate ZMB8232, ZMB8238, ZMB7120, ZMB7427, ZMB8222, ZMB4436, and ZMB8255 to another group.

Through this analysis and farmers' own selection criteria, six maize varieties were selected in Shiwuyunji and Rufunsa. The six maize varieties (ZM8259, ZM6614, ZM8160, ZM5205, ZM6846, and ZM5203) scored high in Shiwuyunji. Of the six selected maize varieties, ZM8259 and ZM6614 were the most preferred by farmers. In Rufunsa, the maize varieties that ranked highly during farmer evaluation were ZM8217, ZM8196, ZM8172, ZM4429, ZM4436, and ZM8174, of which ZM8217 and ZM8196 were outstanding. The preferred maize varieties were superior with respect to earlier maturity, higher grain yield, increased cob size, and increased grain size.

Discussion

The analysis of agro-morphological data in this study indicates that there was significant variation among the maize varieties; their grouping patterns seem to conform to the geographic origin of the collections, suggesting that they could be adapted to specific regions. Based on morphological and reproductive traits, Llaurado and Moreno-Gonzalez (1993) and Ruiz de Galarreta and Alvarez (2001) screened and measured variability of maize germplasm accessions and clustered them into separate groups. PCA indicates that days to 50% tasseling, days to silking, plant height, ear height, and number of leaves above upper ear are the most important descriptors, accounting for more than 50% of the phenotypic variation expressed in the maize accessions; these are therefore the most useful traits for studying the variability of maize populations. Our results suggest the possibility of agro-morphological variation in the maize accessions under study being influenced by specific environmental factors. The results from this study also seem to demonstrate that in addition to the open-pollinated nature of the crop, the role of farmers in the selection process and the crop's adaptation to climatic and environmental conditions may perhaps explain the observed variation in the maize populations (Llaurado & Moreno-Gonzalez, 1993). In a similar manner, Ng'uni et al. (2011) reported the influence of geographical locality for close similarity of sorghum accessions, attributing this pattern to the existence of variety exchange patterns. Categorising germplasm accessions into morphologically similar and, presumably, genetically similar groups (Souza & Sorrells, 1991) is useful for selecting parents for crossing. Crossing germplasm accessions belonging to different groupings could maximize opportunities for transgressive segregation. Considering the higher probability that unrelated genotypes would contribute unique desirable alleles at different loci (Peeters & Martinell, 1989; Beer et al., 1993), the grouping of maize accessions in the present study would be of practical value to breeders in selecting representative accessions for crossing programmes.

Given that climate change and increased genetic erosion due to both natural and human-driven factors seem to be evident and irreversible trends, initiatives focusing on restoration of local germplasm obtained from the national gene bank become necessary. Local crop varieties in farmers' fields evolve with changing climate and are therefore less prone to environmental stresses such as drought. As observed by other authors (Teshome et al. 2001; Newton et al. 2010), genetic variation for stress tolerance is broadly explained by differences among and within traditional crop varieties. The involvement of local farmers through participatory variety selection becomes critical to increasing the chances of acceptance and adoption of crop varieties suitable for specific agro-ecological regions. The selected maize varieties in this study were subsequently involved in the guided participatory seed multiplication programme for distribution to other households in the two areas. Conserved samples of these varieties are readily available to breeders for use in their breeding programmes.

Case Study II: Evaluation of cowpea germplasm for drought tolerance in Botswana

Greenhouse experiment

Plant materials

Twenty cowpea genotypes were obtained from farmers in Hukuntsi (Kalahari Desert), Lecheng, and Makoro (Eastern Central District) and the National Plant Genetic Resources Centre at the Department of Agricultural Research, Ministry of Agricultural Development and Food Security (NPGRC-DAR) in Botswana (Tab. 3). Further, six of the genotypes were tested for drought tolerance in the Kalahari Desert under its adverse environmental conditions.

Study site

The greenhouse experiment at Botswana University of Agriculture and Natural Resources site (24° 38′ 41.5″ S, 25° 54′ 26.46″ E, and 983 m elevation) was conducted from December 2013 through January 2014, where the following average environmental conditions were recorded: 11 hours sunshine duration, 17/31°C minimum and maximum temperatures, and 50% relative humidity. However, the greenhouse temperature was modulated at 20°C minimum and 30°C maximum.

Experimental design and agronomic management

Twenty cowpea genotypes were planted in wooden boxes measuring 117 cm (length) by 85 cm (width) and 12 cm (depth). Seeds were planted at distances of 10 cm between rows and 5 cm between plants. Plants were raised under well-watered conditions until the first trifoliate leaf was fully expanded after about four weeks. Half of the plants were then exposed to mild drought stress by withdrawing irrigation after soil moisture content had reached 50% of field capacity. The other half of the plants were maintained at field capacity moisture content until sampling. Soil moisture was monitored with the MpKit portable soil moisture sensor kit (ICT International, Armidale, New South Wales, Australia) following manufacturer protocol. The experimental design was randomised complete block design (RCBD) and each treatment was replicated four times.

Table 3: Description of 20 cowpea genotypes used for drought tolerance evaluation; germplasm was collected from various sources in Botswana

Serial No	ID No	Genotypes	Source
1	BCA001	Blackeye	NPGRC-DAR
2	BCA002	Speckled Grey-1	Farmer-Hukuntsi
3	BCA003	Makoro	Farmer-Makoro
4	BCA004	Speckled brown-1	Famer-Lecheng
5	BCA005	B 212	NPGRC-DAR
6	BCA006	B069 E	NPGRC-DAR
7	BCA007	B079-C	NPGRC-DAR
8	BCA008	B020-A	NPGRC-DAR
9	BCA009	Mahutohuto	Farmer-Hukuntsi
10	BCA010	B 505A	NPGRC-DAR
11	BCA011	B 500	NPGRC-DAR
12	BCA012	B111-B	NPGRC-DAR
13	BCA013	Tswana	Farmer-Hukuntsi
14	BCA014	E 129	NPGRC-DAR
15	BCA015	E 129 (2)	NPGRC-DAR
16	BCA016	Speckled brown	Farmer-Tshane
17	BCA017	Tswana Red	Farmer-Hukuntsi
18	BCA018	Bo11-A 7	NPGRC-DAR
19	BCA019	Lecheng	Farmer-Lecheng
20	BCA020	E7	NPGRC-DAR

Data collection and analysis

After 11 days, plants were harvested to determine above-ground biomass yield for well-watered controls (BYW) and drought-stressed treatment (BYD). The following indices were calculated as described in Tab. 4: biomass stress susceptibility index (BSSI), relative drought index (RDI), stress tolerance index (STI), tolerance (TOL), mean production (MP), drought resistance index (DI), and biomass reduction (BR). Pearson's correlation coefficients (r) between BYW, BYD, and drought tolerance indices were calculated to determine the most suitable index for monitoring drought.

Field experiment

Plant materials

The field experiment involved six genotypes (BCA001, BCA002, BCA004, BCA009, BCA013, BCA016, BCA019). The genotypes underwent the greenhouse test and were preferred by local farmers; two of them, BCA001 (Blackeye) and BCA013 (Tswana), were varieties released by the Department of Agricultural Research for production and are the most prominent among pulses in the Botswana Agriculture Marketing Board retail shops.

Study site

The Hukuntsi Site (24° 1′ 1″ S, 21° 52′ 8″ E, and 1118 m elevation) is located in the heart of the Kalahari Desert. The soils are characterised as deep sand, generally

Table 4 Description of drought tolerance indices and their definitions used in the study. BYW: biomass yield under well-watered conditions; BYD: biomass yield under drought stress conditions; TOL: tolerance; MP: biomass mean productivity; STI: biomass stress tolerance index; SSI: biomass stress susceptibility index; DI: drought index; and BR: biomass reduction

No.	Index and abbreviation	Formula	Description	Reference
1	Tolerance (TOL)	$BYW - BYD$	A larger value of TOL represents greater sensitivity to drought	Rosielle and Hamblin, (1981)
2	Mean Productivity (MP).	$\frac{BYD + BYW}{2}$	High MP indicate drought tolerance.	Fernandez *et al.*, (1992)
3	Stress tolerance index (STI). High STI indicate more tolerance	$\frac{(BYD \times BYW)}{(B\bar{Y}s^2)}$	High STI indicate more tolerance	Fischer and Maurer, (1978)
4	Stress Susceptibility Index (SSI).	$\frac{1-(BYD/BYW)}{1-(B\bar{Y}D/\ B\bar{Y}W)}$	SSI<1 indicate more resistance to drought	Fischer and Maurer, (1978)
5	Drought Resistance Index (DI).	$[(BYWxBYD)/BYW/B\bar{Y}D]$	High DI indicate drought tolerance	Fischer and Maurer, (1978)
6	Biomass Reduction (BR).	$\frac{(BYW - BYD]}{BYW}$	Low BR indicates drought tolerance	Harb *et al.*, (2010)

exceeding 60 metres; they are low in organic matter and could be extremely dry. During the December 2013 through May 2014 experimental period, an on-site rain gauge recorded a total precipitation of 132 mm. A weather station located 2 km away from the farm site recorded averages of 10 hours sunshine duration, 18°C minimum and 31°C maximum air temperature, and 68% average humidity during the period.

Experimental design and agronomic management

The experiment was planted in a farmer's field on 15 December 2014 in Hukuntsi (Kalahari Desert). The experimental design was randomised complete block design (RCBD) and each treatment was replicated four times. Weeding was carried out 30 days after sowing. In the months of January and February 2015, an extended period of lack of rainfall and high heat imposed severe drought stress and plant death was observed at the vegetative stage.

Table 6: Correlation coefficient between biomass yield and tolerance indices measured from 20 cowpea genotypes tested in the greenhouse. * and ** significant at 0.05 and 0.01 levels. BYW: biomass yield under well-watered conditions; BYD: biomass yield under drought stress conditions; TOL: tolerance; MP: biomass mean productivity; STI: biomass stress tolerance index; SSI: biomass stress susceptibility index; DI: drought index; and BR: biomass reduction (see Tab. 4).

	BYW	BYD	TOL	MP	STI	SSI	DI	BR
BYW	1							
BYD	0.506*	**1**						
TOL	0.970**	0.28	**1**					
BMP	0.980**	0.660*	0.90**	**1**				
BSTI	-0.660**	0.540*	-0.81**	-0.52*	**1**			
BSSI	-0.430*	0.25	-0.55*	-0.31	0.84**	**1**		
DI	-0.660**	0.25	-0.81**	-0.52*	1.00**	0.84**	**1**	
BR	0.700**	- 0.180*	0.83**	0.57**	-0.99**	-0.85**	-0.99**	**1**

Data collection and analysis

At approximately 55 days after sowing, data on plant survival was scored as the ratio of dead to total plants in a plot. This was expressed as plant drought survival percentage (PDS%). We used ANOVA with Fisher's LSD post-hoc test to analyse data. Means were considered significantly different when $p \leq 0.05$. To determine relationships between individual drought indices and PDS%, linear response models were fitted and relationships were considered statistically significant at $p \leq 0.05$.

Table 5: Drought tolerance indices of 20 cowpea genotype under stress and non-stress conditions in a greenhouse. BYW: biomass yield under well-watered conditions; BYD: biomass yield under drought stress conditions; TOL: tolerance; MP: biomass mean productivity; STI: biomass stress tolerance index; SSI: biomass stress susceptibility index; DI: drought index; and BR: biomass reduction

Genotypes	BYW	BYD	TOL	MP	STI	SSI	DI	BR
BCA001	8.098	2.29	5.808	5.194	16.086	0.546	3.016	0.637
BCA002	6.664	2.434	4.23	4.549	5.844	0.288	1.096	0.519
BCA003	7.718	2.725	4.993	5.222	5.649	0.333	1.059	0.545
BCA004	4.823	1.672	3.151	3.248	5.547	0.355	1.04	0.552
BCA005	1.891	2.223	-0.332	2.057	18.809	3.072	3.527	-0.337
BCA006	6.549	1.867	4.682	4.208	4.561	0.54	0.855	0.602
BCA007	4.446	1.03	3.416	2.738	3.707	0.665	0.695	0.627
BCA008	2.224	2.236	-0.012	2.23	4.525	3.952	0.848	-0.333
BCA009	5.53	2.528	3.002	4.029	7.314	0.5	1.371	0.505
BCA010	2.814	1.305	1.509	2.06	7.42	-0.215	1.391	0.337
BCA011	4.185	1.641	2.544	2.913	6.274	0.178	1.176	0.496
BCA012	3.86	1.529	2.331	2.695	6.338	0.161	1.188	0.472
BCA013	5.953	1.939	4.014	3.946	5.211	0.424	0.977	0.566
BCA014	3.163	1.488	1.675	2.326	7.527	-0.262	1.411	0.341
BCA015	4.59	1.57	3.02	3.08	5.473	0.371	1.026	0.571
BCA016	6.542	2.288	4.254	4.415	5.596	0.345	1.049	0.512
BCA017	3.952	1.569	2.293	2.806	6.717	0.424	1.259	0.416
BCA018	6.173	1.879	4.294	4.026	4.87	0.488	0.913	0.599
BCA019	6.518	2.165	4.353	4.342	5.315	0.404	0.996	0.56
BCA020	4.174	1.339	2.835	2.757	5.133	0.439	0.962	0.594

Results

Drought tolerance indices for cowpea

Biomass yield under both well-watered (BYW) and drought stress (BYD) conditions were used to calculate the drought indices (Tab. 5). There was a positive and significant correlation between BYW and BYD ($r^2 = 0.50$). Significant correlations were observed between BYW and all indices (TOL, MP, STI, SSI, DI, and BR), whereas BYD was correlated with MP only (Tab. 5). Correlation analysis between the indices showed that that TOL was significantly correlated with all other indices; MP significantly correlated with TOL, STI, and DI, but not with SSI. The STI index significantly correlated with all other indices (Tab. 6). The SSI significantly correlated with TOL, STI, DI, and BR, but not with MP. The DI index significantly correlated with all other indices. A strong positive correlation between STI and DI was observed.

Performance of cowpea genotypes under greenhouse conditions

The genotypes with high values of STI and DI were considered tolerant to drought stress under greenhouse conditions. Drought-tolerant genotypes were (Blackeye), BCA009 (Mahutohuto), and BCA005 (B212), whereas BCA006 (B069), BCA007 (B079-C), BCA008 (B020-A), and BCA013 (Tswana) were drought sensitive.

Performance of cowpea genotypes under field conditions

Under severe drought stress in the field, there was a mean survival of 71%. The highest survival rates were attained by BCA001 (Blackeye) (96.4%), BCA009 (Mahutohuto) (96.2%), and BCA016 (Speckled brown) (90.6%), while the lowest survival rates were recorded for (BCA019) (38.8%) and BCA002 (Speckled grey-1) (42.9%) (Fig. 3). The genotypes with the highest survival rates under field conditions were considered drought tolerant.

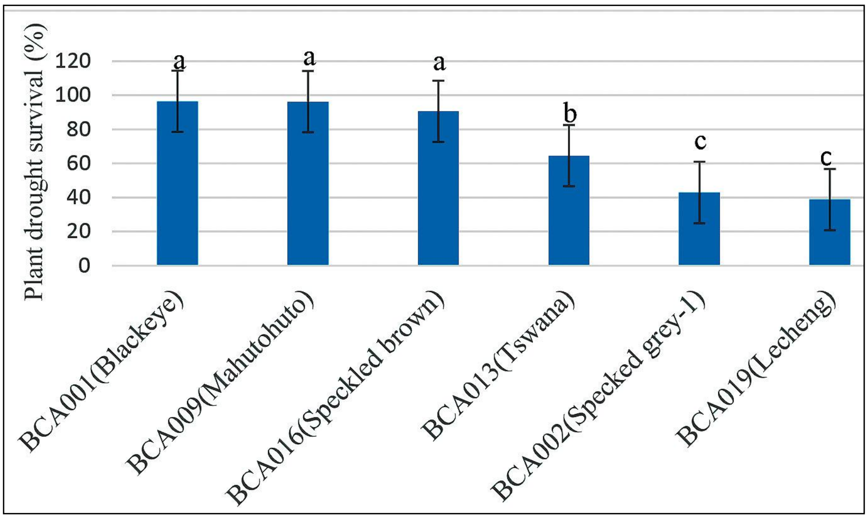

Figure 3: Effects of severe drought stress on the survival of six cowpea genotypes in the field in Hukuntsi (Kalahari Desert). At 55 days after planting, total number of plants was scored and survival (%) was calculated as the proportion of living to total number plants in a sampled row.

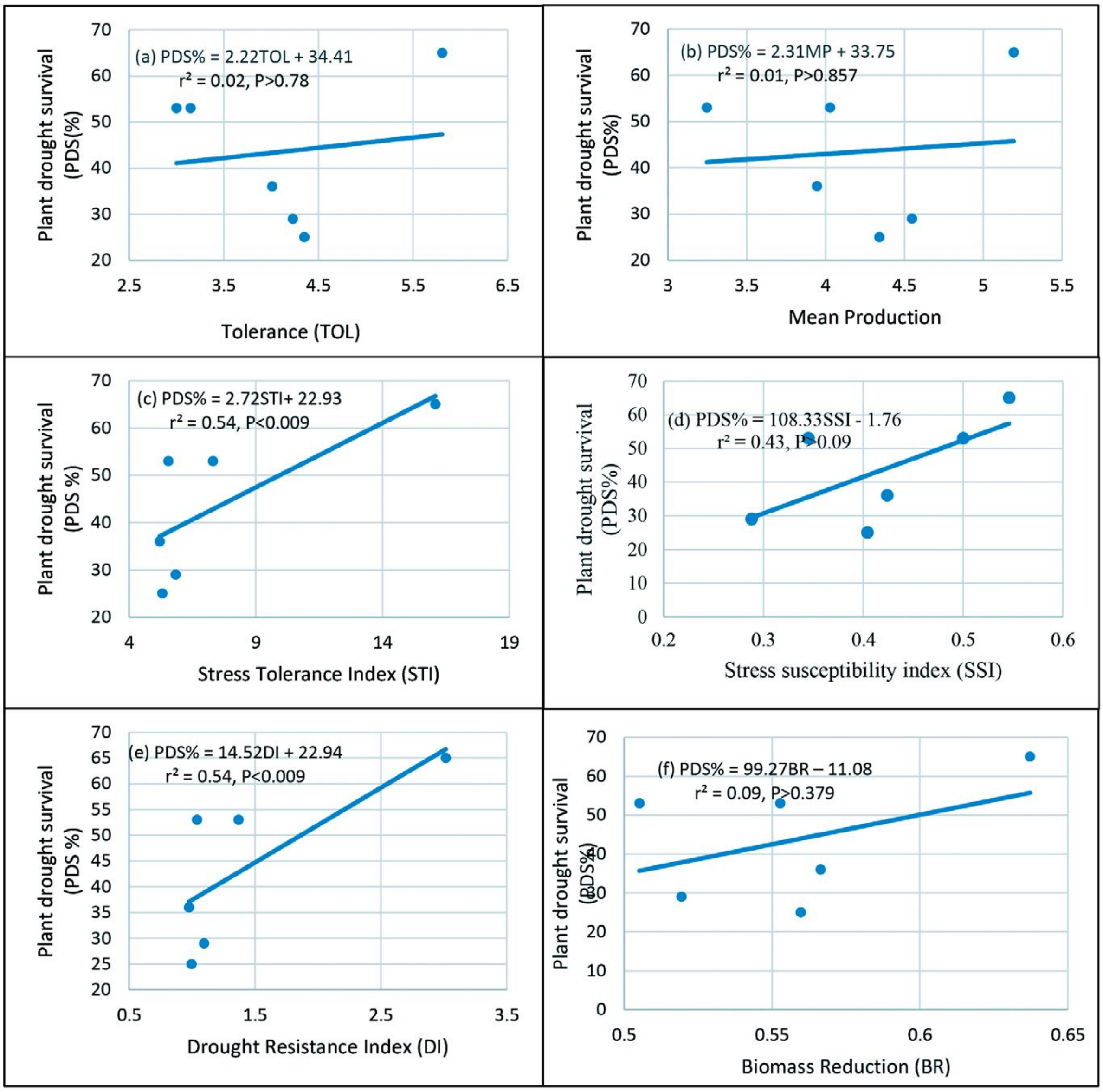

Figure 4: Relationships between drought tolerance indices and plant survival (%) in the field. Plants were exposed to drought stress for 11 days and drought tolerance indices were calculated and described as section 5.4.

Correlation between greenhouse and field data on plant survival under severe drought

A cross-check of the response of the genotypes to mild drought stress in the greenhouse study with the severe drought stress under field conditions confirmed that BCA001 (Blackeye), BCA009 (Mahutohuto), and BCA016 (Speckled brown) were more drought-tolerant than BCA013 (Tswana), BCA019 (Lecheng), and BCA002 (Speckled grey-1) (Fig. 4). PDS% was significantly correlated with STI ($r^2 = 0.54$, $p < 0.009$) and DI ($r^2 = 54$, $p < 0.009$) and not with TOL, MP, SSI, or BR.

Discussion

The greenhouse study indicated a high correlation between TOL and STI; moreover, it indicated that the two indices significantly correlated with all other indices. STI was also correlated with BYW and BYD, which showed its reliability and suggested that it may be the most suitable selection index for cowpea under greenhouse conditions. A suitable index must have a significant correlation with yield under both conditions (Mitra, 2001), which suggests that it can select genotypes under either drought or well-watered conditions. Other studies have identified STI to be a suitable index for drought tolerance selection for cowpea (Belko et al., 2014, Batieno et al., 2016) and for wheat (Naghavi et al., 2013).

The Kalahari Desert environment presented an opportunity to select cowpea for drought tolerance, where plant death occurred as a result of low rainfall and high temperatures in the months of January 2014. The survival rate (PDS%) of the different genotypes ranged from 38% to 96%, indicating that there is genetic variability for drought tolerance among the tested germplasm. Further, the PDS% results showed that the BCA001 (Blackeye), BCA009 (Mahutohuto), and BCA016 (Speckled brown) genotypes were more drought tolerant than BCA013 (Tswana), BC002 (Speckled grey-1), and BCA019 (Lecheng). It is worth noting that the two landraces, BCA009 (Mahutohuto) and BCA016 (Speckled brown), were collected from farmers in Hukuntsi (Kalahari Desert) and are popular among the local farmers for production, which indicates their adaptability. The variety BCA001 (Blackeye) was selected for Botswana's local arid environment by the Department of Agricultural Research.

Regression analysis between the greenhouse study and PDS% revealed significant association between STI and DI, which indicates the reliability of the two in selecting cowpea genotypes for the more hostile field environment. The results further confirm the utility of STI as the index most suitable for cowpea drought tolerance selection. The STI index has also been suggested for heat temperature tolerance selection (Porch, 2006; Porch et al., 2009), which is characteristic of the study area.

General conclusions and recommendations

Participatory evaluation of germplasm is important to assess plants' specific area suitability and to encourage farmer adoption of varieties perceived to be suitable for local conditions. Maize varieties that were selected by farmers due to their early maturation and perceived hardy grain type for withstanding postharvest storage pests in Shiwuyunji and Rufunsa have the potential to be suitable for other areas with similar agro-ecological characteristics. The cowpea study in Botswana has identified three genotypes, BCA001 (Blackeye), BCA009 (Mahutohuto), and BCA016 (Speckled brown) as on-farm drought tolerant. These can be recommended for production in the Hukuntsi (Kalahari Desert) environment to mitigate recurring drought, which is a permanent feature of the area and likely to increase in the future. The maize and cowpea genetic materials that were identified as suitable for production in Zambia and Botswana could be also be used for crop improvement programs in the SASSCAL region or parts of Sub-Saharan Africa with similar agro-ecologies. Involvement of smallholder farmers through participatory variety selection of promising crop varieties increases chances of adoption of better-performing candidate varieties that meet farmers' specific criteria in their specific localities.

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References

Batieno, J.B., Tignegre, J-B., Hamadou, S., Hamadou, Z., Oudraogo, T.J., Danquah, E. & Ofori, K. (2016) Field assessment of cowpea genotypes for drought tolerance. *International Journal of Sciences: Basic and Applied Research,* **30,** 358–369.

Beer, S.C., Goffreda, J., Phillips, T.D., Murphy, J.P. & Sorrells, M.E. (1993) Assessment of genetic variation in *Avena sterilis* using morphological traits, isozymes, and RFLPs. *Crop Science*, **33,** 1386–1393.

Belko, N., Cisse, N., Diop, N.N., G., Zombre, S., Thiaw, S., Muranaka, S. & Ehlers, J.D. (2014) Selection for post-flowering drought resistance in short- and medium- duration cowpeas using stress tolerance indices. *Crop Science,* **54,** 25–33.

Fernandez, G.C. (1992) Effective selection criteria for assessing plant stress tolerance. Proceedings of the International Symposium on Adaptation of Vegetables and Other Food Crops in Temperature and Water Stress. AVRDC, Tainan, Taiwan, 257–270.

Fischer, R.A. & Maurer, R. (1978) Drought resistance in spring wheat cultivars: I. Grain yield response. *Australian Journal of Agricultural Research,* **29,** 897–907.

Foyer, C.H., Lam, H-M. & Nguyen, H.T. (2016) Neglecting legumes has compromised human health and sustainable food production. *Nature Plants,* **2,** 1–10.

Harb, A., Krishnan, A., Ambavaram, M.M.R. & Pereira, A. (2010) Molecular and physiological analysis of drought stress in *Arabidopsis* reveals early responses leading to acclimation in plant growth. *Plant Physiology*, **154,** 1254–1271.

International Board for Plant Genetic Resources (IBPGR) (1991) Descriptors for maize. International Maize and Wheat Improvement Center, Mexico City/International Board for Plant Genetic Resources, Rome.

Intergovernmental Panel on Climate Change (IPCC) (2007b) Climate change impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK.

Lindner, M., Maroschek M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M.J. & Marchetti, M. (2010) Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management,* **259,** 698–709.

Langyintuo, A.S. & Mungoma C. (2008). The effect of household wealth on the adoption of improved maize varieties in Zambia. *Food Policy,* **33,** 550–559.

Llaurado, M. & Moreno-Gonzalez, J. (1993) Classification of northern Spanish populations of maize by methods of numerical taxonomy: I. Morphological traits. *Maydica,* **38**, 15–21.

Marshall, D.R. & Brown, A.H.D. (1975) Optimum sampling strategies in genetic conservation. *Crop genetic resources for today and tomorrow*. (ed. by O.H. Frankel and J.G. Hawkes), pp. 53–80. Cambridge University Press, London.

Mitra, J. (2001). Genetics and genetic improvement of drought resistance in crop plants. *Current Science in India,* **80,** 758–762.

Ministry of Agriculture (MoA). (2010). Guidelines for Integrated Support Programme for Arable Agricultural Development. Government Publishers, Gaborone, Botswana.

Naghavi, M.R., Aboughadareh, A.P. & Khalili, M. (2013). Evaluation of drought tolerance indices for screening some of corn (*Zea Mays L.*) cultivars under environment conditions. *Notulae Scientia Biologia,* **5,** 388–393.

Newton, A.C., Akar, T., Baresel, J.P., Bebeli, P.J., Bettencourt, E., Bladenopoulos, K.V., Czembor, J.H., Fasoula, D.A., Katsiotis, A., Koutis, K., Koutsika-Sotiriou, M., Kovacs, G., Larsson, H., Pinheiro de Carvalho, M.A.A., Rubiales, D., Russell, J., Dos Santos, T.M., & Vaz Patto, M.C. (2010) Cereal landraces for sustainable agriculture. A review. *Agronomy for Sustainable Development,* **30,** 237–269.

Ng'uni, D., Mulatu, G. & Bryngelsson, T. (2011) Genetic diversity in sorghum (*Sorghum bicolor* [L.] Moench) accessions of Zambia as revealed by simple sequence repeats (SSR). *Hereditas,* **148,** 52–62.

Peeters, J.P. & Martinelli, J.A. (1989) Hierarchical cluster analysis as a tool to manage variation in germplasm collections. *Theoretical and Applied Genetics*, **78,** 42–48

Porch, T.G. (2006) Application of stress indices for heat tolerance screening of common bean (*Phaseoleus vulgaris*). *Journal of Agronomy and Crop Sciences,* **192,** 390–394.

Porch, T.G., Ramirez, V.H., Santana D. & Harmsen, E.W., (2009) Evaluation of drought tolerance in common bean germplasm in Juana Diaz, Puerto Rico. *Journal of Agronomy and Crop Sciences,* **195,** 1–7.

Ramirez-Villegas, J. & Thornton, P.K. (2015) Climate change impacts on African crop production. CCAFS Working Paper no. 119. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark.

Rosielle, A.A. & Hamblin, J. (1981) Theoretical aspects of selection for yield in stress and non-stress environments. *Crop Science*, **21,** 943–946.

Rohlf, F.J. (1998) NTSYS-PC 2.2. Numerical taxonomy and multivariate analysis system. Exeter Software, Applied Biostatistics, New York.

Ruiz de Galarreta, J.I. & Alvarez, A. (2001) Morphological classification of maize landraces from northern Spain. *Genetic Resources and Crop Evolution,* **48,** 391–400.

Siddique, K.H.M., Johansen, C. & Turner, N.C. (2012) Innovations in agronomy for food legumes. *Agronomy for Sustainable Development,* **32,** 45–64.

Stringer, L.C., Dyer, J.C., Reed, M.S. & Dougill, A.J. (2009) Adaptation to climate change, drought, and desertification: Local insights to enhance policy in southern Africa. *Environmental Science and Policy,* **12,** 748–765.

Souza, E. & Sorrells, M.E. (1991) Relationships among 70 North American oat germplasm: I. Cluster analysis using quantitative traits. *Crop Science*, **31,** 599–605.

Teshome, A., Brown, A.H.D. & Hodgkin, T. (2001) Diversity in landraces of cereal and legume crops. *Plant Breeding Review,* **21,** 221–261.

Tuberosa, R. (2012). Phenotyping for drought tolerance of crops in the genomics era. *Frontiers in Physiology,* **3,** 347.

Tubiello, F.N., Soussana, J-F. & Howden, S.M. (2007) Crop and pasture response to climate change. *Proceedings of the National Academy of Sciences USA,* **104,** 19686–19690.

References [CrossRef]

Batieno, J.B., Tignegre, J-B., Hamadou, S., Hamadou, Z., Oudraogo, T.J., Danquah, E. & Ofori, K. (2016) Field assessment of cowpea genotypes for drought tolerance. *International Journal of Sciences: Basic and Applied Research*, **30,** 358–369.

Beer, S.C., Goffreda, J., Phillips, T.D., Murphy, J.P. & Sorrells, M.E. (1993) Assessment of genetic variation in *Avena sterilis* using morphological traits, isozymes, and RFLPs. *Crop Science*, **33,** 1386–1393. CrossRef

Belko, N., Cisse, N., Diop, N.N., G., Zombre, S., Thiaw, S., Muranaka, S. & Ehlers, J.D. (2014) Selection for post-flowering drought resistance in short- and medium- duration cowpeas using stress tolerance indices. *Crop Science*, **54,** 25–33. CrossRef

Fernandez, G.C. (1992) Effective selection criteria for assessing plant stress tolerance. Proceedings of the International Symposium on Adaptation of Vegetables and Other Food Crops in Temperature and Water Stress. AVRDC, Tainan, Taiwan, 257–270.

Fischer, R.A. & Maurer, R. (1978) Drought resistance in spring wheat cultivars: I. Grain yield response. *Australian Journal of Agricultural Research*, **29,** 897–907. CrossRef

Foyer, C.H., Lam, H-M. & Nguyen, H.T. (2016) Neglecting legumes has compromised human health and sustainable food production. *Nature Plants*, **2,** 1–10. CrossRef

Harb, A., Krishnan, A., Ambavaram, M.M.R. & Pereira, A. (2010) Molecular and physiological analysis of drought stress in *Arabidopsis* reveals early responses leading to acclimation in plant growth. *Plant Physiology*, **154**, 1254–1271. CrossRef

International Board for Plant Genetic Resources (IBPGR) (1991) Descriptors for maize. International Maize and Wheat Improvement Center, Mexico City/International Board for Plant Genetic Resources, Rome.

Intergovernmental Panel on Climate Change (IPCC) (2007b) Climate change impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK.

Lindner, M., Maroschek M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M.J. & Marchetti, M. (2010) Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management*, **259,** 698–709. CrossRef

Langyintuo, A.S. & Mungoma C. (2008). The effect of household wealth on the adoption of improved maize varieties in Zambia. *Food Policy*, **33,** 550–559. CrossRef

Llaurado, M. & Moreno-Gonzalez, J. (1993) Classification of northern Spanish populations of maize by methods of numerical taxonomy: I. Morphological traits. *Maydica*, **38**, 15–21.

Marshall, D.R. & Brown, A.H.D. (1975) Optimum sampling strategies in genetic conservation. *Crop genetic resources for today and tomorrow*. (ed. by O.H. Frankel and J.G. Hawkes), pp. 53–80. Cambridge University Press, London.

Mitra, J. (2001). Genetics and genetic improvement of drought resistance in crop plants. *Current Science in India*, **80,** 758–762.

Ministry of Agriculture (MoA). (2010). Guidelines for Integrated Support Programme for Arable Agricultural Development. Government Publishers, Gaborone, Botswana.

Naghavi, M.R., Aboughadareh, A.P. & Khalili, M. (2013). Evaluation of drought tolerance indices for screening some of corn (*Zea Mays L.*) cultivars under environment conditions. *Notulae Scientia Biologia*, **5,** 388–393.

Newton, A.C., Akar, T., Baresel, J.P., Bebeli, P.J., Bettencourt, E., Bladenopoulos, K.V., Czembor, J.H., Fasoula, D.A., Katsiotis, A., Koutis, K., Koutsika-Sotiriou, M., Kovacs, G., Larsson, H., Pinheiro de Carvalho, M.A.A., Rubiales, D., Russell, J., Dos Santos, T.M., & Vaz Patto, M.C. (2010) Cereal landraces for sustainable agriculture. A review. *Agronomy for Sustainable Development*, **30,** 237–269. CrossRef

Ng'uni, D., Mulatu, G. & Bryngelsson, T. (2011) Genetic diversity in sorghum (*Sorghum bicolor* [L.] Moench) accessions of Zambia as revealed by simple sequence repeats (SSR). *Hereditas*, **148,** 52–62. CrossRef

Peeters, J.P. & Martinelli, J.A. (1989) Hierarchical cluster analysis as a tool to manage variation in germplasm collections. *Theoretical and Applied Genetics*, **78,** 42–48. CrossRef

Porch, T.G. (2006) Application of stress indices for heat tolerance screening of common bean (*Phaseoleus vulgaris). Journal of Agronomy and Crop Sciences*, **192,** 390–394. CrossRef

Porch, T.G., Ramirez, V.H., Santana D. & Harmsen, E.W., (2009) Evaluation of drought tolerance in common bean germplasm in Juana Diaz, Puerto Rico. *Journal of Agronomy and Crop Sciences*, **195,** 1–7. CrossRef

Ramirez-Villegas, J. & Thornton, P.K. (2015) Climate change impacts on African crop production. CCAFS Working Paper no. 119. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark.

Rosielle, A.A. & Hamblin, J. (1981) Theoretical aspects of selection for yield in stress and non-stress environments. *Crop Science*, **21,** 943–946. CrossRef

Rohlf, F.J. (1998) NTSYS-PC 2.2. Numerical taxonomy and multivariate analysis system. Exeter Software, Applied Biostatistics, New York.

Ruiz de Galarreta, J.I. & Alvarez, A. (2001) Morphological classification of maize landraces from northern Spain. *Genetic Resources and Crop Evolution*, **48,** 391–400. CrossRef

Siddique, K.H.M., Johansen, C. & Turner, N.C. (2012) Innovations in agronomy for food legumes. *Agronomy for Sustainable Development*, **32,** 45–64. CrossRef

Stringer, L.C., Dyer, J.C., Reed, M.S. & Dougill, A.J. (2009) Adaptation to climate change, drought, and desertification: Local insights to enhance policy in southern Africa. *Environmental Science and Policy*, **12,** 748–765. CrossRef

Souza, E. & Sorrells, M.E. (1991) Relationships among 70 North American oat germplasm: I. Cluster analysis using quantitative traits. *Crop Science*, **31,** 599–605. CrossRef

Teshome, A., Brown, A.H.D. & Hodgkin, T. (2001) Diversity in landraces of cereal and legume crops. *Plant Breeding Review*, **21,** 221–261. CrossRef

Tuberosa, R. (2012). Phenotyping for drought tolerance of crops in the genomics era. *Frontiers in Physiology*, **3,** 347. CrossRef

Tubiello, F.N., Soussana, J-F. & Howden, S.M. (2007) Crop and pasture response to climate change. *Proceedings of the National Academy of Sciences USA*, **104,** 19686–19690. CrossRef

Food security

Grain yield water use efficiency of cowpea (*Vigna unguiculata* L. Walp.) in response to planting dates in Botswana

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Abstract: Ag Southern Africa is characterized by a high degree of rainfall variability affecting agriculture among other sectors. The timing of the rainfall has shifted as a result of climate change, and variability is expected to be even higher in the future. This threatens grain production, which is dependent on rainfall; strategies such as choice of planting date and crop selection based on water use efficiency could help farmers mitigate some of these impacts. This study investigated the effect of planting dates and genotypic differences on grain yield, water use, and water use efficiency of cowpea. Six cowpea genotypes were planted at four different times (November, December, January, and February). The results indicate that cowpea grown in January used moderate amounts of plant-available water, significantly producing a higher average grain yield of 335.2 kg/ha with a water use efficiency of 3.72 kg/ha.mm-1. BCA001 (blackeye) exhibited the highest grain yield and water use efficiency in all the planting dates, indicating broad adaptation, while landrace BCA019 (speckled grey cowpea), has the potential to be bred for drought tolerance and be released as a variety thanks to its earliness and high water use efficiency.

Resumo: A África Austral é caracterizada por um elevado grau de variabilidade da precipitação, afectando a agricultura, entre outros sectores. A altura das chuvas mudou devido às alterações climáticas e prevê-se que a variabilidade será ainda maior. Isto ameaça a produção de grãos, a qual é dependente das chuvas. Logo, estratégias, tais como a escolha da data da plantação e a selecção da cultura com base na eficiência do uso da água, poderão ajudar os agricultores a mitigar alguns desses impactos. Este estudo investigou o efeito das datas de plantação e diferenças genotípicas na productividade e eficiência do uso da água do feijão-frade. Seis genótipos de feijao-frade foram plantados em quatro alturas diferentes (Novembro, Dezembro, Janeiro e Fevereiro). Os resultados indicam que o feijao-frade crescido em Janeiro utiliza quantidades moderadas da água disponível, produzindo maiores productividades médias, de 335,2Kg/ha, com uma eficiência do uso da água de 3,72Kg/ha.mm-1. O BCA001 (Blackeye) exibiu a maior productividade e eficiência do uso da água em todas as datas de plantação, indicando uma adaptação geral, enquanto que a variedade autóctone BCA019 (Speckled grey cowpea) tem o potencial de ser criada para a tolerância à seca e de ser lançada como uma variedade devido à sua precocidade e elevada eficiência do uso da água.

Introduction

Agricultural productivity is believed to be under threat as a result of global change (Metz et al., 2007). This change has resulted in seasonal variability of rainfall, which places farmers at a greater risk of low production and crop losses, especially in sub-Saharan Africa (SADC, 2015). With its semi-arid climate, Botswana has a mean annual rainfall ranging from over 650 mm in the north-east to less than 250 mm in the south-west. The national average rainfall is 475 mm per year, which is half of the global average annual rainfall (CSO, 2013). The rainy season starts either early or much later than the traditional dates, and this has challenged farmers with respect to planting dates. Poor planting date selection may subject crops to water and heat stress during dry spells and critical growth stages, resulting in reduced yield; thus, there is a need for crop species that can efficiently use available water (Lemos & Dilling, 2007). Farmers (landraces) and plant breeders (varieties) have successfully selected life cycle duration and phenology to maximize both the range of environments in which crops grow and their yields, at least for current climates. The major challenge for crop improvement is how to plan for future climate change. According to FAO (2011), enhancing food security while contributing to mitigating climate change requires the transition to agricultural production systems that are more productive and use inputs more efficiently. One strategy that farmers can use to maintain or increase crop yields in the face of the changing climate is the use of drought-tolerant, water use–efficient crop varieties and adjusting of planting dates (Rockstrom & Barron, 2007).

Cowpea is one crop that is indigenous to sub-Saharan Africa, and many wild relatives of the species are found in abundance. In Botswana it is an important multipurpose food legume and the third most cultivated crop after maize and sorghum (CSO, 2013). Cowpea grows best at day temperatures of 25–35°C with an average rainfall of less than 500 mm per annum, and its tolerance to drought is attributed to traits that enable it to capture and use water more efficiently than other legumes (Madamba et al., 2006; Singh et al., 2002). Water use efficiency, which is defined by Tambussi et al. (2007) as the ratio of dry matter produced to the amount of water used, is an important physiological characteristic related to the ability of the crop to cope with water stress. It is an important trait for drought tolerance improvement and can be enhanced by selection of crop varieties and agronomic practices such as time of sowing based on available water, increasing seasonal evapotranspiration (Singh et al., 2012).

Studies by Patel et al. (2008) indicated that water use and water use efficiency in terms of grain yield are influenced by sowing dates; early-sown cowpea genotypes had higher water use efficiency than the late-sown ones. Similar findings were reported by Awasthi et al. (2007) in Indian mustard. According to Bhale & Wanjari (2009), the influence of sowing dates on water use efficiency of crops has implications for the ability of crops to withstand drought conditions. Therefore, characterising crop water use response for cowpea in dryland farming for different planting dates has a positive effect on food security. This study investigated the effect of planting date on grain yield and water use of cowpea under rainfed conditions. Evaluating the WUE of cowpea for different planting dates will generate information useful for the production of cowpea genotypes better adapted to the challenging environment and that exhibit a low demand for water, thereby addressing the rainfall variability associated with climate change. Information generated will address adaptation to changes in climate that influence temperature, season length, optimal planting dates, the occurrence of drought, and crop durations.

Materials and methods

Plant material

Six cowpea genotypes were sourced from farmers and the National Plant Genetic Resources Centre (NPGRC), Department of Agricultural Research (DAR), under the Ministry of Agricultural Development and Food Security in Botswana. Two of the varieties are released varieties by the DAR, whereas the other four are farmer-selected landraces from Hukuntsi (24°1′1″ S, 21°52′8″ E) in the Kalahari Desert and Lecheng (22°39′55″ S, 27°13′12″ E) in the Central District of Botswana (Tab. 1). Selection of both released varieties and genotypes was based on the preferences of local subsistence farmers. Seed materials for these genotypes are available at the Botswana University of Agriculture and Natural Resources (BUAN) Plant Physiology Laboratory, and farmers and researchers can obtain through the corresponding author.

Field experiment

During the 2014/15 season, a field trial was planted at the Botswana University of Agriculture and Natural Resources on-station farm in Sebele (24°34′25″ S, 25°58′00″ E). The site climate is characterized as semi-arid (Luhanga & Andringa, 1990). The soils are shallow, ferruginous tropical soils consisting mainly of medium to coarse grains and sandy loams with low water-holding capacity and subject to crusting after heavy rains (De-Wilt & Nachtengaele, 1996). Cowpea was sown on four dates (10 November, 16 December, 13 January, 6 February) in 2014/15 in a split plot design, with planting dates as the main factor and genotypes as subplots replicated four times. The planting dates chosen represented early (10 November), moderately early (16 December), optimal (13 January), and late (6 February) planting. These were based on recommendations from the Ministry of Agricultural Development and Food Security. Each plot had an area of 9.6 m^2 with a spacing of 0.75 m between rows and 0.20 m between plants. Seedlings were established under irrigation to allow for maximum crop stand until four weeks after planting. Thereafter, the experiment was maintained under rain-fed conditions until data collection was completed.

Data collection

Two inner rows in a plot were tagged, and data were collected on flowering, maturity, and pod grain yield. The number of days to 50% flowering was determined when 50% of plants were at the full bloom (R2) stage (when 50–100% of flowers were open). Days to maturity was recorded when the pods had reached the harvest maturity (RH) stage (when 80% of pods were mature in colour). Seed yield was determined during harvest and values were converted to kg/ha.

During the cropping season, daily temperature was recorded at Sir Seretse

Serial No	ID No	Genotype	Source
1	BCA001	Blackeye[a]	NPGRC-DAR
2	BCA002	Speckled grey[b]	Hukuntsi
3	BCA009	Tswana brown[b]	Hukuntsi
4	BCA013	Tswana cream[a]	NPGRC-DAR
5	BCA016	Speckled brown[b]	Lecheng
6	BCA019	Speckled grey[b]	Lecheng

Table 1: Description of the genotypes used for water use efficiency (WUE) evaluation in Sebele. Germplasm was collected from various sources in Botswana. Superscripts indicate that the genotype is a released variety (a) and a landrace (b).

Khama International Airport, located 3 km from the site, and monthly averages were calculated. Rainfall data were collected from a site-located rain gauge, and averages were calculated for the entire growing period.

Crop water use

Soil water content (SWC) was measured at the beginning and end of the experiment using a soil moisture probe metre (MPM-160-B, ICT International Pty Ltd) to calculate crop water use (WU) using the water balance equation by Songsri et al. (2009):

$$WU = I + R + \Delta S$$

where *I* is the irrigation amount (mm), *R* is rainfall (mm), and *ΔS* is the difference between the soil moisture at harvest and at planting. Water use efficiency was defined as the ratio of crop grain yield (GY) to total amount of water used using the following equation by Songsri et al. (2009):

$$WUE = \frac{GY}{WU}$$

Data analysis

The collected data were subjected to the statistical analysis of variance by using SAS 9.4. Means were tested and separated using Tukey's honestly significant difference (HSD) post hoc test to analyse differences between experimental factors (planting dates) and treatments (genotypes) at $p = 0.05$.

Results

Weather conditions

Observed weather characteristics during the study showed a pattern of uneven rainfall distribution and midseason dry spells that were often accompanied by high temperatures (Fig. 1). February was the hottest month, with the succeeding months getting cooler. As a result, the December planting occurred under heat and drought stress. Generally, the temperatures neither exceeded nor went below the cowpea growing temperature thresholds during the growing season for any of the planting dates, which made them suitable for growth. Differences in cumulative rainfall were evident among the different planting dates. The cumulative rainfall amounts were 152 mm, 163.1 mm, 176.4 mm, and 177.2 mm for the November, December, January, and February planting dates, respectively. For all planting dates, the recorded rainfall was less than the crop water requirement, which exposed the cowpea to water deficit.

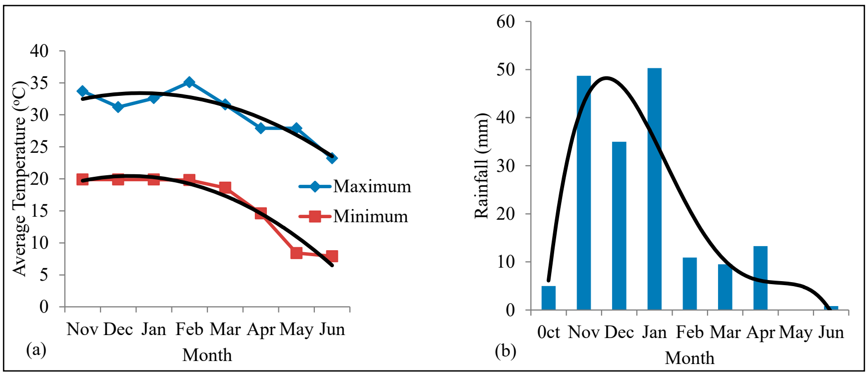

Figure 1: Mean minimum and maximum temperature (a) and rainfall (b) for 2014–2015 season in Sebele, Gaborone, Botswana. The season was characterised by an uneven rainfall distribution and mid-season dry spells, which were often accompained by high temperatures.

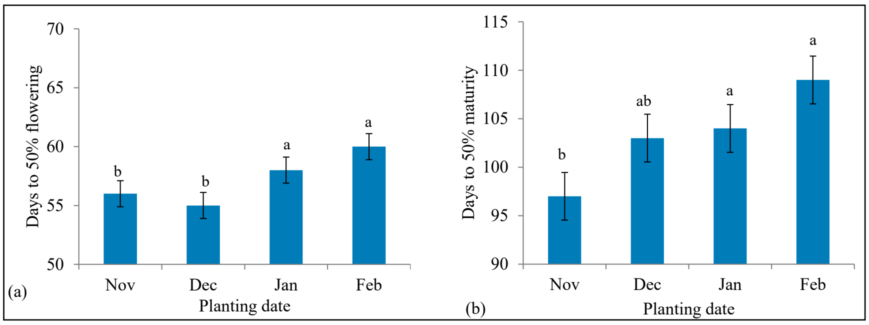

Figure 2: Effect of planting date on mean days to 50% flowering (a) and 50% maturity (b) of cowpea genotypes. The comparison was made between planting dates irrespective of the cowpea genotypes. Error bars indicate standard error of the means. Same letters on the bars of each genotype indicate nonsignificant differences ($p > 0.05$) between irrigated and rainfed conditions by Tukey's HSD post hoc test.

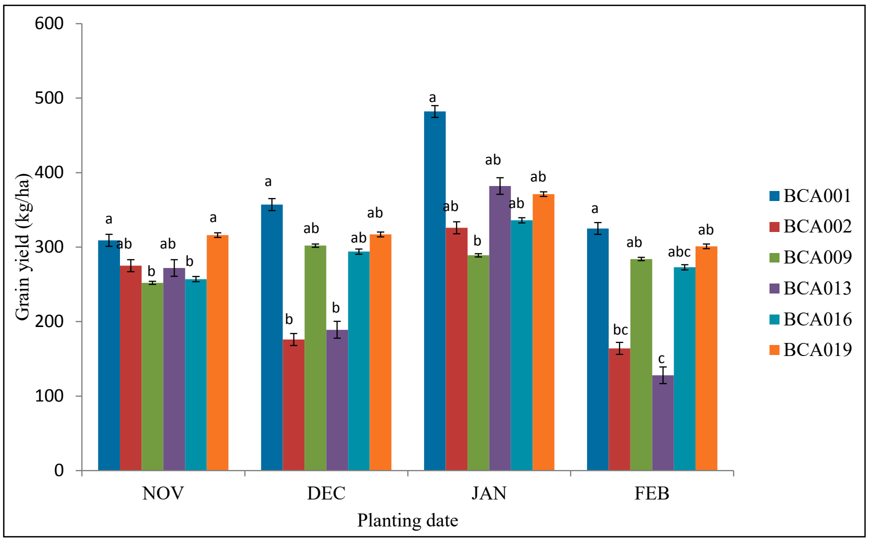

Figure 3: Mean grain yield of cowpea genotypes as influenced by planting date. The highest mean grain yield was recorded in January, and BCA001 had the highest across all the dates in the 2014–2015 season. The dates used were a recommendation from the Ministry of Agricultural Development and Food Security in Botswana. Error bars indicate standard error of the means. Same letters on the bars of each genotype indicate nonsignificant differences ($p < 0.05$) between irrigated and rainfed conditions by Tukey's HSD post hoc test.

Phenological development

Cowpea planted early (November and December) had a significantly shorter growing season than with late planting (January and February) (Fig. 2). The longest time to flowering and maturity was observed when planting was initiated in February, whereas the opposite was true for November planting. With regard to genotypic performance, a significant difference ($p < 0.05$) among genotypes irrespective of planting dates was also noted in terms of flowering and maturity (Tab. 2). BCA001 and BCA019 flowered and matured early compared to BCA009 and BCA013, which were late in these two phenological traits.

Grain yield

Planting dates significantly influenced cowpea grain yield. The average seed yield ranged from 128 kg/ha to 482 kg/ha. Cowpea planted in January had the highest grain yield, whereas the early and late dates had lower yield, February being the lowest (Fig. 3). Genotypes significantly ($p < 0.05$) varied in grain yield performance for different dates. BCA001 and BCA019 maintained high yield stability among all the dates whereas BCA013 had a significant drop in yield at late planting. BCA001 produced a significantly higher grain yield for all planting dates, indicating that the variety is an ideotype possessing superior grain-yielding ability with broad adaptation traits.

Water use and water use efficiency

Generally WU was suboptimal for all planting dates owing to below-average rainfall. This confirms drought experienced by the genotypes for all the dates. There was a significant variation in WU with respect to planting dates (Fig. 4a). Cowpea planted in November used 50% of plant-available water, while 80%, 65%, and 63% were used for the succeeding dates, respectively. No significant differences were recorded in terms of water use for the January and February planting dates. Genotypic differences were observed for the different sowing dates; generally BCA001 used less water, followed by BCA019 and BCA002 across all planting dates (Fig. 5). For WUE, there was a

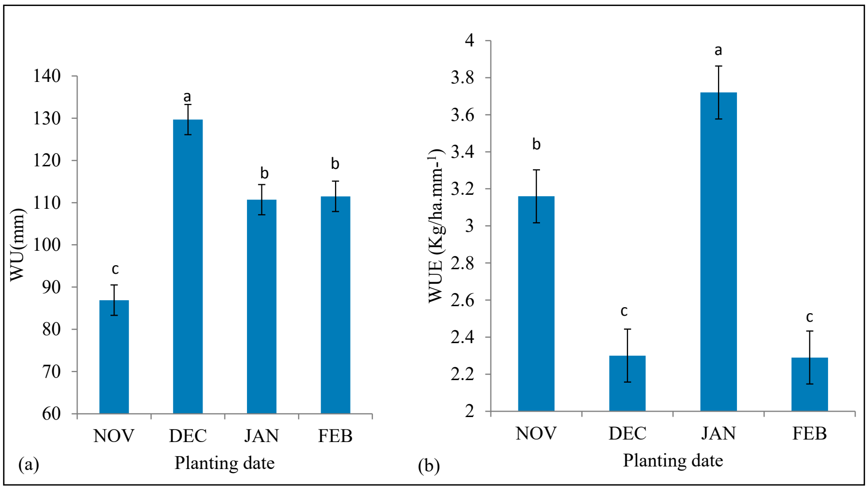

Figure 4: Mean water use (a) and water use efficiency (b) of cowpea as influenced by planting date. Water use was calculated using the soil water balance method, and water use efficiency was computed as the ratio of grain yield to water use. Soil water was measured using a soil moisture probe meter (MPM-160-B, ICT International Pty Ltd). Error bars indicate standard error of the means. Same letters on the bars of each genotype indicate nonsignificant differences ($p < 0.05$) between irrigated and rainfed conditions by Tukey's HSD post hoc test.

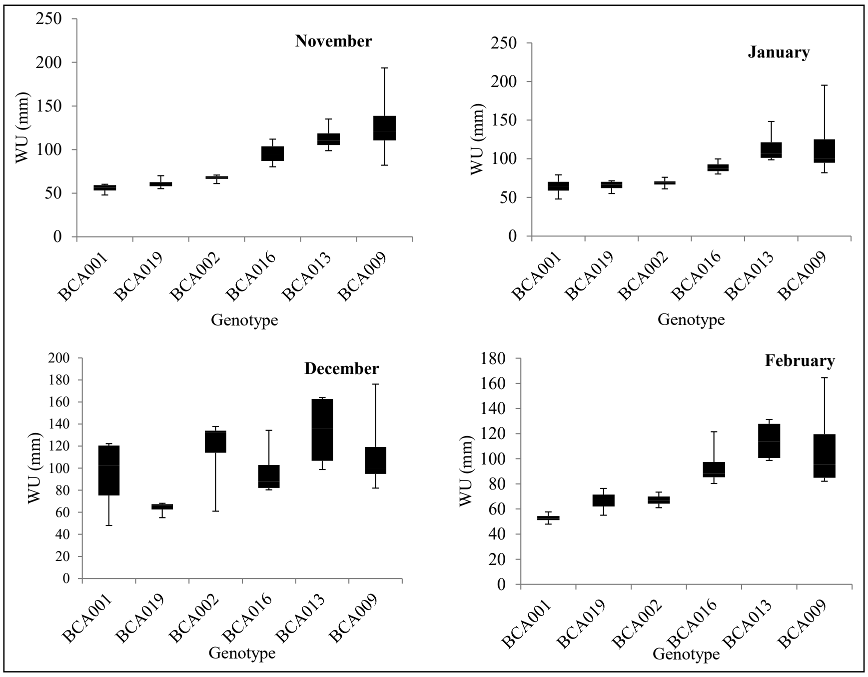

Figure 5: Distribution of water use by genotype for different planting dates. Box plots were used to show the distribution, and less water was used by cowpea planted in November.

Genotype	Days to 50% flowering	Days to maturity
BCA001	45^{d}	72^{e}
BCA002	56^{c}	99^{c}
BCA009	79^{a}	143^{a}
BCA013	60^{b}	113^{b}
BCA016	58^{b}	112^{b}
BCA019	46^{d}	87^{d}
LSD (0.05)	**2.08**	**4.1**

Table 2: Average number of days to 50% flowering and 50% maturity of cowpea genotypes. The averages were pooled data from four planting dates (November, December, January and December) in 2014 to 2015 season. Means followed by the same letter within a column are not significantly different ($p \leq 0.05$) based on the Tukey's HSD post hoc test. BCA001 and BCA019 had the shortest growing season, whereas BCA009 had the longest growing season.

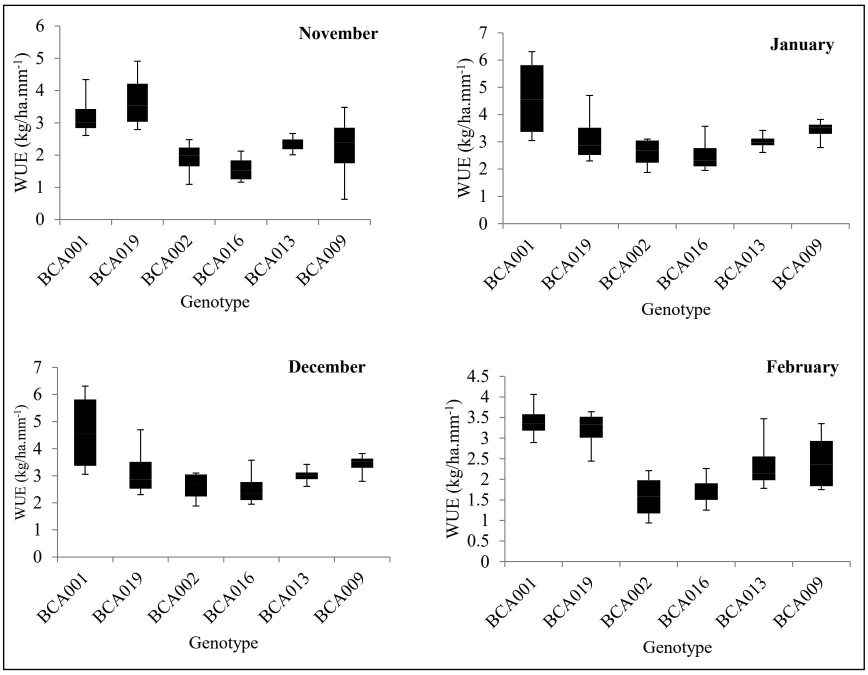

Figure 6: Distribution of water use efficiency by genotype for different planting dates. Box plots were used to show the distribution. BCA001 was the most efficient, with a wider variation.

significant variation across the planting dates, with January being the highest (average of 3.36kg/ha.mm^{-1}) and February being the lowest (2.27 kg/ha.mm^{-1}) (Fig. 4b). There is apparent distinction of WUE between genotype across the planting dates (Fig. 6). BCA001 had the highest WUE for most planting dates, followed by BCA019, whereas BCA016 was the least efficient. On average BCA001 had WUE of 3.78 kg/ha.mm^{-1}, whereas BCA016 was less efficient, with an average of 2.14 kg/ha.mm^{-1}.

Discussion

The study found significant differences among six cowpea genotypes for grain yield, water use, and water use efficiency when tested for four planting dates. There were fewer days to 50% flowering and maturity in early (November and December) planted cowpea. This trend might be ascribable to the higher temperatures and low rainfall recorded between January and February 2015, which was the onset of flowering for early planting. In return, the longer duration of flowering and maturity for late-planted crops could be due to the exposure of plants to fewer high-temperature days. Temperature is undoubtedly the dominant factor that affects flowering and maturity, accelerating flowering and maturity in legumes to avoid pre- and post-anthesis water stress (Agele et al., 2002; Paradwa et al., 2016). While most literature indicates that early planting increased yield in soybean and cowpea (Shegro et al., 2010; Akande et al., 2012), the results obtained here suggest the opposite. The lowest grain yield for early planting could be attributed to lower rainfall received during the growth period, as most plants were dead at the reproductive stage. According to Mugalavai et al. (2008), yields may suffer with either a late onset or early cessation of the growing season, as well as with a high frequency of damaging dry spells within the growing season. For February planting, shortened day length could be the reason for lower yields because when the duration of growth is short, the production of photosynthates becomes low, which affects crop performance negatively (Banik et al., 2000). Generally, most cowpea genotypes showed inconsistency in seed yield. This is an indication of sensitivity to the environment, mainly temperature and rainfall, which caused an interaction between genotype and planting date. These results suggest that most genotypes had the capacity to yield depending on the planting date. Low amounts of rainfall coupled with high temperature for the November planting resulted in less water available for plants and thus lower WU. Although cumulative rainfall was highest for February, planting in this month resulted in a decrease in WUE, which may be attributed to a proportionately larger reduction in seed yield in relation to consumptive water use, as reported by Patel et al. (2008). Cowpea sown in January experienced more evenly distributed rainfall than the earlier dates, 'although [rainfall] was below the recommended amounts of water for optimal growth,' as well as temperatures that were suitable for growth. Shifting the planting time of crops from a period with high evaporative demand to one with low demand is likely to reduce WU, thereby enhancing WUE. This could explain the high WUE recorded in January-planted cowpea (Singh et al., 2012).

Conclusion

This study demonstrated that genotypes and planting date significantly influenced cowpea water use, grain yield, and water use efficiency. Cowpea sown in January matured early, had high grain yield, and was more water use efficient. Amongst the released varieties, BCA001, with a lower number of days to maturity, proved better in terms of grain yield and WUE compared to BCA013 and other landraces across the planting dates. BCA001 could be recommended for any planting date, but for best results planting in January is highly recommended. The landrace BCA019 performed better than all other landraces and also than the released variety BCA013, making it a potential tool for water use efficiency breeding. Although it is a released variety, BCA013 needs to be studied further for drought tolerance and for future improvement. Results from this study suggest that WUE can be enhanced through the selection of varieties and sowing date. Present findings were based on one-year experimentation, and hence this study can be repeated with more genotypes in different agro-ecological zones of Botswana.

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References

Agele, S.O., Olufayo, A. & Iremiren, G.O. (2002). Effects of season of sowing on water use and yield of tomato in humid south Nigeria. *African Crop Science,* **10**, 213–237.

Akande, S.R., Ajayi, S. A., Adetumbi, J.A., Adeniyan, O.N., Ogunbodede, B.A., Owolade, O.F. & Olakojo, S.A. (2012). Planting date effects on cowpea seed yield and quality at southern guinea Savanna of Nigeria. *Proofs,* **34**, 79–88.

Awasthi, U.D., Singh, R.B. & Dubey, S.D. (2007). Effect of sowing date and moisture conservation practice on growth and yield of Indian mustard (Brassica juncea) varieties. *Indian Journal of Agronomy,* **52**, 151–153.

Banik, P., Bagchi, D.K., Sasmal, P.K. & Ghosal, M.N. (2000). Evaluation of Legume growth. *Crop Science Journal*, **185**, 9–14.

Bhale, V.M. & Wanjari, S.S. (2009). Conservation Agriculture: a new paradigm to increase resource use efficiency. *Indian Journal of Agronomy,* **54**, 167–177.

CSO (2013). *2012 annual agricultural survey report.* Government Printer, Gaborone, Botswana.

De-Wilt, P.V. & Nachtengaele, F.O. (1996). *Explanatory notes on soil map of the Republic of Botswana.* Soil Mapping and Advisory Services. Government Printer Press, Gaborone.

FAO (2011). *Climate change, water and food security.* FAO Water Report 36. FAO, Rome.

Lemos, M.C. & Dilling, L. (2007). Equity in forecasting climate: can science save the world's poor? *Science Public Policy,* **34**, 109–116.

Luhanga, P.V. & Andringa, J. (1990). Characteristics of solar radiation at Sebele, Gaborone, Botswana. *Solar Energy,* **44**, 77–81.

Madamba, R., Grubben, G.J., Asante, I.K. & Akromah, R. (2006). Vigna unguiculata (L.) Walp. *Plant Resources for Tropical Africa 1.Cereals and Pulses.* (ed. by M. Brink and G. Belay), pp. 221–229, PROTA Foundation, Wageningen, Netherlands.

Metz, B., Davidson, O.R. Bosch, P.R. & Dave, L.A. (eds.) (2007). *Climate change 2007: mitigation of climate change. Contribution of Working Group III to the fourth assessment report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, UK.

Mugalavai, E.M., Kipkorir, E.C., Raes, D. & Rao, M.S. (2008). Analysis of rainfall onset, cessation and length of growing season for western Kenya. *Agricultural and Forest Meteorology,* **148**, 1123–1135.

Paradwa, C., Karavina, C., Kamota, A., Mandumbu, R. & Nyemba, N. (2016). Evaluation of seasonal rainfall changes on the growth performance of Vigna unguiculata (cowpeas) in Zimbabwe. *Academic Journal of Agricultural Research,* **4**, 67–71.

Patel, I.C., Patel , B.S., Patel, M.M., Patel, A.G. & Tikka, S.B. (2008). Effect of irrigation schedule, dates of sowing and genotypes on yield, water use efficiency and water extraction pattern of cowpea. *Journal of Food Legumes,* **21**, 132–137.

Rockstrom, J. & Barron, J. (2007). Water productivity in rainfed systems: overview of challenges and analysis of opportunities in water scarcity–prone savannas. *Irrigation Science,* **25**, 299–311.

SADC (2015). *Food Security Early Warning System: Agromet update 2014/15 agricultural season.* SADC, Gaborone, Botswana.

Shegro, A., Atilaw, A., Pal, U.R. & Geleta, N. (2010). Influence of varieties and planting dates on growth and development of soybean (*Glycine max* L. Merr) in Metekel zone, North Western Ethiopia. *Journal of Agronomy,* **9**, 146–156.

Singh, A., Aggarwal, N., Aulakh, G.S. & Hundal, R. (2012). Ways to maximize the water use efficiency in field crops. *General Journal of Agricultural Sciences,* **2**, 108–129.

Singh, B.B., Ehler, E.J., Sharma, B. & Freire Filho, F.P. (2002). Recent progress in cowpea breeding. *Challenges and opportunities for enhancing sustainable cowpea production* (ed. by C.A. Fatokun, S.A. Tarawali, B.B. Singh, P.M. Kormawa and M. Tamo), pp. 22-40, Proceedings of the World Cowpea Conference III held at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. IITA, Ibadan, Nigeria.

Songsri, P., Jogloy, S., Holbrook, C. C., Kesmala, T., Vorasoot, N., Patanothai, A. & Akkasaeng, C. (2009). Association of root, specific leaf area and SPAD chlorophyll meter reading to water use efficiency of peanut under different available soil water. *Agricultural Water Management,* **96**, 790–798.

Tambussi, E.A., Bort, A.J. & Araus, J.L. (2007). Water use efficiency in C3 cereals under Mediterranean conditions: a review of physiological aspects. *Annals of Applied Biology,* **150**, 307–321.

References [CrossRef]

Agele, S.O., Olufayo, A. & Iremiren, G.O. (2002). Effects of season of sowing on water use and yield of tomato in humid south Nigeria. *African Crop Science*, **10**, 213–237.

Akande, S.R., Ajayi, S. A., Adetumbi, J.A., Adeniyan, O.N., Ogunbodede, B.A., Owolade, O.F. & Olakojo, S.A. (2012). Planting date effects on cowpea seed yield and quality at southern guinea Savanna of Nigeria. *Proofs*, **34**, 79–88.

Awasthi, U.D., Singh, R.B. & Dubey, S.D. (2007). Effect of sowing date and moisture conservation practice on growth and yield of Indian mustard (Brassica juncea) varieties. *Indian Journal of Agronomy*, **52**, 151–153.

Banik, P., Bagchi, D.K., Sasmal, P.K. & Ghosal, M.N. (2000). Evaluation of Legume growth. *Crop Science Journal*, **185**, 9–14. CrossRef

Bhale, V.M. & Wanjari, S.S. (2009). Conservation Agriculture: a new paradigm to increase resource use efficiency. *Indian Journal of Agronomy*, **54**, 167–177.

CSO (2013). *2012 annual agricultural survey report.* Government Printer, Gaborone, Botswana.

De-Wilt, P.V. & Nachtengaele, F.O. (1996). *Explanatory notes on soil map of the Republic of Botswana.* Soil Mapping and Advisory Services. Government Printer Press, Gaborone.

FAO (2011). *Climate change, water and food security.* FAO Water Report 36. FAO, Rome.

Lemos, M.C. & Dilling, L. (2007). Equity in forecasting climate: can science save the world's poor? *Science Public Policy*, **34**, 109–116. CrossRef

Luhanga, P.V. & Andringa, J. (1990). Characteristics of solar radiation at Sebele, Gaborone, Botswana. *Solar Energy*, **44**, 77–81. CrossRef

Madamba, R., Grubben, G.J., Asante, I.K. & Akromah, R. (2006). Vigna unguiculata (L.) Walp. *Plant Resources for Tropical Africa 1.Cereals and Pulses.* (ed. by M. Brink and G. Belay), pp. 221-229, PROTA Foundation, Wageningen, Netherlands.

Metz, B., Davidson, O.R. Bosch, P.R. & Dave, L.A. (eds.) (2007). *Climate change 2007: mitigation of climate change. Contribution of Working Group III to the fourth assessment report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, UK.

Mugalavai, E.M., Kipkorir, E.C., Raes, D. & Rao, M.S. (2008). Analysis of rainfall onset, cessation and length of growing season for western Kenya. *Agricultural and Forest Meteorology*, **148**, 1123–1135. CrossRef

Paradwa, C., Karavina, C., Kamota, A., Mandumbu, R. & Nyemba, N. (2016). Evaluation of seasonal rainfall changes on the growth performance of Vigna unguiculata (cowpeas) in Zimbabwe. *Academic Journal of Agricultural Research*, **4**, 67–71.

Patel, I.C., Patel , B.S., Patel, M.M., Patel, A.G. & Tikka, S.B. (2008). Effect of irrigation schedule, dates of sowing and genotypes on yield, water use efficiency and water extraction pattern of cowpea. *Journal of Food Legumes*, **21**, 132–137.

Rockstrom, J. & Barron, J. (2007). Water productivity in rainfed systems: overview of challenges and analysis of opportunities in water scarcity–prone savannas. *Irrigation Science*, **25**, 299–311. CrossRef

SADC (2015). *Food Security Early Warning System: Agromet update 2014/15 agricultural season.* SADC, Gaborone, Botswana.

Shegro, A., Atilaw, A., Pal, U.R. & Geleta, N. (2010). Influence of varieties and planting dates on growth and development of soybean (*Glycine max* L. Merr) in Metekel zone, North Western Ethiopia. *Journal of Agronomy*, **9**, 146–156. CrossRef

Singh, A., Aggarwal, N., Aulakh, G.S. & Hundal, R. (2012). Ways to maximize the water use efficiency in field crops. *General Journal of Agricultural Sciences*, **2**, 108–129.

Singh, B.B., Ehler, E.J., Sharma, B. & Freire Filho, F.P. (2002). Recent progress in cowpea breeding. *Challenges and opportunities for enhancing sustainable cowpea production* (ed. by C.A. Fatokun, S.A. Tarawali, B.B. Singh, P.M. Kormawa and M. Tamo), pp. 22-40, Proceedings of the World Cowpea Conference III held at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. IITA, Ibadan, Nigeria.

Songsri, P., Jogloy, S., Holbrook, C. C., Kesmala, T., Vorasoot, N., Patanothai, A. & Akkasaeng, C. (2009). Association of root, specific leaf area and SPAD chlorophyll meter reading to water use efficiency of peanut under different available soil water. *Agricultural Water Management*, **96**, 790–798. CrossRef

Tambussi, E.A., Bort, A.J. & Araus, J.L. (2007). Water use efficiency in C3 cereals under Mediterranean conditions: a review of physiological aspects. *Annals of Applied Biology*, **150**, 307–321. CrossRef

Sustaining rural livelihoods through an integrated landscape approach

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Abstract: Our socioeconomic field studies in the Zambezi region of Namibia show that the agricultural system is characterized by extremely low diversity, not providing sufficient nutrients to ensure food security for a growing population. We find that programs to protect wildlife and forests are not harmonizing well with smallholder farming. While politicians and external stakeholders pay attention to biodiversity in protected areas, they largely ignore agrobiodiversity. Agricultural policy in particular is more likely to limit resilient landscape development, as shown, for example, by targeted subsidies for maize cultivation. Regarding the much-discussed link between development and conservation, existing approaches such as community-based natural resource management (CBNRM) and joint management of fisheries resources do not take due account of the importance of benefit sharing and food security. The economic incentives provided by these systems in the form of hunting quotas or recreational angling operations neither are sufficient to halt the progressive loss of biodiversity nor offer alternatives to the exploitation of natural resources on which the local population highly depends. The paper discusses selected research findings and suggests a more holistic approach to landscape management.

Resumo: Os nossos estudos socio-económicos na região do Zambezi, Namíbia, mostram que o sistema agrícola é caracterizado por uma diversidade extremamente baixa, não fornecendo nutrientes suficientes para assegurar a segurança alimentar de uma população em crescimento. Verificamos que os programas para a protecção da vida selvagem e florestas não estão a harmonizar bem com a agricultura de subsistência. Enquanto que os políticos e as partes interessadas externas prestam atenção à biodiversidade em áreas protegidas, estes ignoram em grande parte a agrobiodiversidade. A política agrícola em particular tem maior probabilidade de limitar o desenvolvimento de paisagens resilientes, tal como visto, por exemplo, nos subsídios direccionados para o cultivo do milho. Quanto à muito discutida ligação entre o desenvolvimento e a conservação, as abordagens existentes, tais como a Gestão de Recursos Naturais Comunitários (CBNRM) e a gestão conjunta dos recursos piscatórios, não têm em conta a importância da partilha de benefícios e a segurança alimentar. Os incentivos económicos oferecidos por estes sistemas sob a forma de quotas de caça ou operações de pesca recreativa, não são suficientes para travar a perda progressiva da biodiversidade, nem oferecem alternativas para a exploração dos recursos naturais, dos quais a população local está altamente dependente. O artigo discute determinados resultados da investigação e sugere uma abordagem mais holística para a gestão da paisagem.

Introduction

The SASSCAL region hosts farming systems habitually consisting of mosaics of cleared farming land, forests, and water bodies, together providing multiple ecosystem services to heterogeneous groups of stakeholders. Various forms of community involvement in fisheries, forestry, and wildlife management have developed in the region. Despite the popularity of community-based programs, however, the overall impact of communities' natural resource management on rural development and the natural environment remains unclear (Humavindu & Stage, 2015; Lewins et al., 2014; Riehl et al., 2015; Silva & Mosimane, 2012). Whereas in some regions of Namibia wildlife populations have increased and tourism is developing (Naido et al., 2016), drastic declines in wildlife populations are occurring in Zambia's game management areas as a result of poaching and escalating land use conflicts (Duffy & Humphreys, 2017; Nyirenda et al., 2017). Human-wildlife conflicts are also reported for villages in Botswana and conservancies in northern Namibia. Women-headed households are particularly affected by high crop losses caused by migrating herds of elephants, as they have less access to compensation and receive little help because of their low status (Gupta, 2013; Khumalo & Yung, 2015). As a result, it is controversially debated whether resources in the region should be used primarily for food production, for nature conservation purposes, or even to promote the coexistence of wildlife and livestock (FAO, 2017; Fynn et al., 2016).

Similar conflicts of interest over the use of natural resources for food or their protection for the benefit of tourism also exist in the field of fisheries management (Abbott et al., 2007; Tweddle et al., 2015). Fish stocks, located in the Zambezi River and across the floodplains in the Zambezi Region, suffer from overfishing and a lack of coordinated management with cross-border Zambia. Conservation efforts in one country, such as establishing protected breeding areas for fish, are often undermined by activities in the other country. Little is also yet known about the status of inland fishing in sub-Saharan Africa and the contribution of small fish, known as 'kapenta' or 'chisense', to the diets of local people. Small fish, sundried and eaten whole, make a very important contribution to a healthy diet, but they are hardly included in the catch statistics (Kolding et al., 2016a; Kolding et al., 2016b). There are, however, controversial views on appropriate management; whereas some experts advocate the management of individual species (e.g., by means of catch controls and selective fishing), other scientists see the need for habitat protection and balanced fishing (e.g., the conservation of wetlands and floodplains as the most productive aquatic systems, where fish come with the rains).

A general problem of natural resource management is the division of responsibilities for different resources among different authorities, particularly the legislative separation between hunting, fishing, and farming (Kolding et al., 2016b). Emerging research on social-ecological systems (SES) has advocated the shift of resource management away from segregated top-down control measures towards integrated, dynamically responsive approaches aimed at improving the resilience of whole landscapes through softer, less intrusive interventions (Daron et al., 2015; Ostrom, 2013).

In Namibia, we observe that the livelihoods of individual households in most cases depend on a mixture of agriculture, extraction of forest products, and fisheries. Households use the diverse services of the ecosystem to manage permanent risks of crop failure and food insecurity. Yet interventions addressing nutrition security and poverty elimination do not usually take a cross-sectoral approach (De Leon et al., 2016; Fisher et al., 2017). Instead, landscape concepts have become the focus of interest in reconciling nature conservation and rural development by looking at landscape conservation from a people-oriented perspective (Denier et al., 2015; Sayer et al., 2013). In addition, a growing number of publications deal with landscape governance issues (see, for example, Foli et al., 2017; Kozar et al., 2014; Mallet et al., 2016; Reed et al., 2016).

The landscape approach

Unlike a sector perspective, an integrated or multifunctional landscape approach recognizes the complex dynamic processes occurring in a landscape. Considering the complexity and the unpredictable nature of SES, key elements of a landscape approach include adaptive management and learning, multi-stakeholder negotiations, capacity-building knowledge platforms, participatory monitoring, and a transparent pathway of change (Allen & Garmestani, 2015; Reed et al., 2016). Critical barriers to its implementation have been identified in areas of low-cost monitoring and sound impact evaluation (Reed et al., 2016). More empirical research on behavioural theory and decision-making can help to understand adoption processes and better map human behaviour in computer-based SES models (Anderies et al., 2011; Schlüter et al., 2017). A further important research issue in the context of landscape management concerns the development of participatory tools for increasing stakeholders' engagement in landscape governance and reducing imbalances in knowledge and power (Kozar et al., 2014). In this respect, tools such as participatory mapping, behavioural experiments, and role-playing games gain in importance and subsequently provide information to more formal computer-based models,

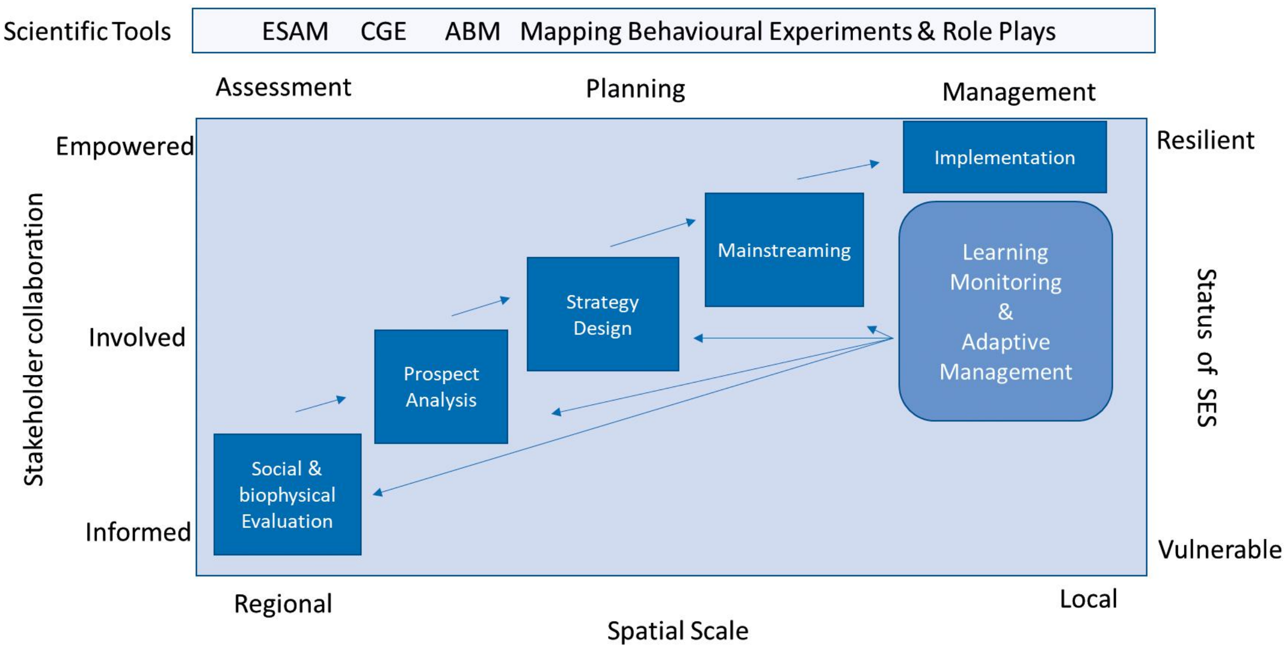

Figure 1: Pathway for implementing an integrated landscape management approach. Source: own figure based on Cowling et al. (2008).

Food security

Figure 2: Role play in a community meeting (a); participatory mapping with a women's group (b). Source: own pictures

which in turn can advise decision-making (Perrotton et al., 2017; Purnomo et al., 2009; Röttgers, 2016; Salvini et al., 2016; Speelman et al., 2014; Villamore et al., 2014).

To understand the challenges of sustainable land use management and address the issue of fair benefit sharing, we applied a set of participatory tools combined with econometric and numerical simulation models. Empirical research reveals that participatory tools facilitate the development of a broader knowledge system through combining traditional and science-based knowledge in a network (Kozar et al., 2014; Scholz et al., 2014). Figure 1 shows a pathway of an integrated landscape approach to managing an SES based on Cowling et al. (2008), who aimed to develop an operational model to implement effective on-the-ground management. The model relies on the findings of numerous empirical studies (see, for example, Foli et al., 2017; Frost et al., 2006).

The scientific tool box depicted in the upper part of the figure shows the methods we applied in our study. These tools comprise environmental social accounting (ESA), computable general equilibrium (CGE) modelling, agent-based modelling (ABM), mapping, behavioural experiments, and role plays. The tools are associated with the three steps of implementing the pathway of a landscape approach comprising assessment, planning, and management. The use of different tools offers advantages for comprehensive research but is of course time-consuming and requires interdisciplinary and transdisciplinary cooperation. Participatory tools, however, are the central component if awareness building and co-management are the goals. Selected methods and results of our research are explained in the following section.

Data and field research

The field studies were conducted in the Sikunga Conservancy, a developing conservancy gazetted in 2009 and located in the Zambezi Region of Namibia. The conservancy covers an area of 287 km^2 which is dominated by floodplains and Mopane woodlands (Mendelsohn, 2010). The region belongs to the Kavango-Zambezi Transfrontier Conservation Area (KAZA TFCA) and is home to rich wildlife and valuable freshwater fish resources (Tweddle et al., 2018). However, the Zambezi Region also suffers from high levels of poverty, malnutrition and income inequality. Moreover, the lack of coordinated management has resulted in an ongoing decrease in livelihoods through deforestation, slash-and-burn cultivation, eroding grazing plains, poaching, and overfishing (Abbott et al., 2009; Tweddle et al., 2015). From approximately 440 households living in 6 villages, 200 households (45%) were randomly sampled in 2012. The survey covered all economic activities with a focus on the collection, consumption, and trade of natural resources and on the nutritional status of the households.

The data were used to construct an environmental social accounting matrix (ESAM) for the study region (Morton et al., 2016). The ESAM is a specification of the System of Environmental and Economic Accounting (SEEA; UNSTAT, 2016) and plays an important role in policy planning and monitoring (Angelsen et al., 2014; De Anguita & Wagner, 2010). The developed matrix represents the total economic transactions within the Sikunga Conservancy for a single year and displays the linkages between economic activities and changes in natural capital in one table. Depending on the research questions, different subregions, sectors, and household groups can be depicted in separate accounts to derive the impact of

Table 1: Nutrition state and household income of the four clustered household groups. Source: own calculations

Daily nutrient intake per adult person per day	Daily minimum requirement	Household group 1 subsistance farmers (deficit in %)	Household group 2 fish & forest users (deficit in %)	Household group 3 skilled off-farm workers (deficit in %)	Household group 4 senior members (deficit in %)
Energy (kcal)	2100	-25.7	-16.6	-26.3	-3.2
Fat (g)	40	-9.3	-2.4	-6.4	33.2
Iodine (μg)	150	-79.9	-50.6	-83.0	-39.0
Iron (μg)	22	-42.4	-34.7	-46.4	-29.8
Protein (g)	52	-13.2	27.7	-46.8	43.5
Vitamin A (μg)	500	-59.1	-52.8	-62.3	-33.4
Zinc (mg)	12	-42.3	-27.5	-44.9	-17.8
Total Income (1000 NAD per household & year) 1€=10NAD in 2012		14.7	24.2	58.9	23.5
Income from:					
Agriculture %		13.4	11.0	10.1	6.7
Fish resources %		5.8	31.2	0.4	2.7
Forest resources %		15.9	10.8	5.9	2.6
Off-farm employment %		43.0	34.0	81.0	38.9
Welfare payments and remittances %		21.9	13.0	2.7	49.1

specific production techniques and different livelihood strategies on the environment. We identify four household groups that differ in terms of their income, consumption, and nutrition situations. The combined representation of monetary and physical accounts within a single matrix is a useful feature to portray the SES of Sikunga Conservancy. In a second research task, the ESAM provides the basic data structure for the design of more advanced socioeconomic simulation models (Gronau et al., 2017). One of the models we have developed is a CGE model that facilitates impact evaluation of different policy interventions. One specification of the model was used to analyse the effect of recreational angling tourism in combination with more restricted fishing policies on freshwater fish stocks and the livelihoods of local households. In further model scenarios, we evaluated a set of agro-ecological food system interventions. In addition to ESAM and CGE analyses, several focus group meetings, behavioural experiments, and role-plays (Fig. 2) have been organized to initiate discussions on sustainable landscape management among community members (Röttgers, 2016; Winter et al., 2017).

Finally, an ABM has been designed to give a picture of current land use activities in the study region and to simulate effects of newly introduced agricultural practices such as agroforestry with *Faidherbia albida*, a nitrogen-fixing tree (Koch, 2017). An ABM has very useful properties for outlining phenomena of emergence in complex social-ecological systems (Moritz et al., 2015; Schlüter et al., 2017). They are well suited for analysing the interaction of heterogeneous agents within a system at different levels of their actions or decision-making processes.

Results and discussion

The ESAM provides valuable insights into the economic and environmental linkages of CBNRM outcomes in the study region. Moreover, the regional representation of the villages in the ESAM framework makes the tool particularly useful in supporting landscape planning. We find that economic output produced from natural resource extraction and harvesting in Sikunga Conservancy is almost double that of both agriculture and all off-farm activities together. With an average yield of 360 kg of maize per hectare, however, the current agricultural system cannot produce even the basic foodstuffs it needs. Up to 80% of individual nutrients are missing in the daily diets, and malnutrition is a serious regional problem. Looking more closely at the nutrition state, consumption analysis at the household level has shown that economic development is not necessarily accompanied by an improvement in nutrition and a more balanced distribution of food in households (Tab. 1). This result is consistent with studies from other countries in sub-Saharan Africa (Brown et al., 2017; Burroway, 2016). Table 1 furthermore shows that household income varies widely at a very low level in absolute terms. All households are below (groups 1, 2, and 4) or just above (group 3) the poverty threshold of US$1.25 per capita per day.

The analysis further reveals that fish resources are harvested at unsustainable rates and slash-and-burn practices destroy about a third of the value of annual growth in forest stocks (Morton et al., 2016). All natural resource–based sectors are strongly interconnected, meaning that bundles of natural resources such as thatching grass, firewood, and fish secure local livelihoods. Opposed to the nature-based sectors, the rest of the economy, particularly off-farm employment in the public sector, is growing separately and somewhat disconnected, missing notable trickle-down effects. This indicates that the growing prosperity of relatively wealthier households is not gradually transferring to the poor. The result has meaningful implications for community development and once more underscores the need for an integrated landscape management approach.

Food security

Although CBNRM is a governance conception aiming to deliver locally adapted sustainable and equitable rural development (Fabricius et al., 2013), our analysis, which is in line with Mosimane and Silva (2015), reveals that Namibian conservancies have not yet developed fair and transparent benefit-sharing systems. A decisive factor for failure is that biased income allocation in favour of asset-rich households causes unsustainable increases in cattle stocks and growing demand for grazing land coupled with increased deforestation. Our analysis confirms the argument of Barendse et al. (2016) that an important limiting factor of CBNRM success is the government's inadequate implementation capacity, implying that local stakeholders have limited opportunities to develop natural resource stewardship. An operational landscape approach therefore requires a multiple-scales polycentric governance architecture as proposed by Ostrom (2012).

Van der Duim et al. (2015) recommended a regional development strategy focusing on nature-based conservation tourism; this strategy is expected to increase rents from natural capital use without putting at risk the natural capital stock. Our CGE model simulations underpin this viewpoint by indicating the very high return to fish allocated to angling tourism (NAD$715) as compared to subsistence fishing (NAD$10) (Gronau et al., 2017). Compared to the partial product analysis conducted by Tweddle et al. (2015), who also calculated a significantly higher value addition of fish in the angling tourism sector, the economy-wide CGE analysis further derives the coupled opportunity costs of nature conservation. If we model the reduction of total catches to a sustainable level, the resultant impact on selected households varies. The model calculates so-called opportunity costs reflecting households' individual utility loss as a result of the intervention. This information may be used to negotiate compensation payments necessary to make the intervention acceptable to the groups affected by the intervention in different ways. In any case, reducing fishing will make a negative contribution to the already poor food situation and will therefore require accompanying measures.

To compensate for the general nutrient deficit in soils and in food in sub-Saharan Africa, it is strongly recommended to invest in a more diversified agricultural system by increasing the contribution of legumes and trees on farms (Kuyah et al., 2016; Masso et al., 2017; Oborn et al., 2017). The results of our ABM simulations show that investments in agroforestry have a positive income effect in addition to improving soil fertility; the net present value is positive and the cost-benefit ratio is significantly higher than 1.0 compared to continuous maize production without trees. Given the very low incomes of all households, however, start-up aid in the form of microfinance must be provided, since the positive effects of an investment in agroforestry will be felt only after about 11 years (Koch, 2017).

As pointed out by FAO (2014) and Snapp & Pund (2017), a growing number of research papers document the substantial contribution of smallholder agro-ecological production systems to food security and food sovereignty. Although these complex agro-ecosystems have a high level of biodiversity and resilience based on traditional knowledge systems, they have not been sufficiently recognized and developed as a source of inspiration for the design of agricultural systems and for the creation and innovation of scientific knowledge (Altieri et al., 2012; Tittonell, 2014). Research in our study region reveals that traditional knowledge and social capital are slowly disappearing. One cause surely is improper agricultural policy — for instance, subsidizing maize production with the consequence of replacing diverse farming systems by maize monoculture, and moreover creating new financial dependencies along the maize value chain. A landscape approach aims at bringing together competing stakeholders through tools fostering communication and working out a common vision of an area (Perrotton et al., 2017; Salvini et al., 2016). Regarding common rules, our behavioural experiment indicates that communication indeed performs at least as well as strong enforcement (Röttgers, 2016). The development of science-based role plays for negotiations in business and political contexts is one of the services offered by Harvard Law School in the program on negotiation (PON, 2017); correspondingly adapted tools could also be applied in the CBNRM context of developing countries. With the aim of resolving conflicts, environmental games provide an opportunity to discuss the natural, social and political dimensions of political disputes, for example in the field of transboundary water management and climate change adaption (Rumore et al., 2016). There are numerous examples of the willingness of decision makers to participate in such activities, and research on the impact of role-playing on conflict resolution continues. Thus, codesigned framed role plays could also become a standard component of land use management in rural communities to motivate the exchange of knowledge and the adoption of improved farming systems.

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References

Allen, C.R. & Garmestani, A.S. (2015) Adaptive management. *Adaptive management of social–ecological systems* (ed. by C.R. Allen & A.S. Garmestani), pp. 1–10. Springer, Dordrecht, The Netherlands. http://dx.doi.org/10.1007/978-94-017-9682-8_1

Altieri, M., Funes-Monzote, F. & Petersen, P. (2012) Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. *Agronomy for Sustainable Development*, **32**, 1–13. doi:10.1007/s13593-011-0065-6

Anderies, J.M., Janssen, M.A., Bousquet, F., Cardenas, J.C., Castillo, D., Lopez, M.-C., Tobias, R., Vollan, B. & Wutich, A. (2011) The challenge of understanding decisions in experimental studies of common pool resource governance. *Ecological Economics*, **70**, 1571–1579.

Angelsen, A., Jagger, P., Babigumira, R., Belcher, B., Hogarth, N. J., Bauch, S. & Wunder, S. (2014) Environmental income and rural livelihoods: a global comparative analysis. *World Development*, **64(Suppl 1)**, S12–S28.

Barendse, J., Roux, D., Currie, B., Wilson, N. & Fabricius, C. (2016) A broader view of stewardship to achieve conservation and sustainability goals in South Africa. *South African Journal of Science*, **112**, 15.

Brown, C., Ravallion, M. & van de Walle, D. (2017) *Most of Africa's nutritionally vulnerable women and children are not found in poor households.* Guide Working Paper Series no. 2. Georgetown University Initiative on Innovation, Development and Evaluation, Washington, DC. https://gui2de.georgetown.edu

Burroway, R. (2016) Empowering women, strengthening children: a multi-level analysis of gender inequality and child malnutrition in developing countries. *Gender and food: from production to consumption and after* (ed. by M.T. Segal & V. Demos), pp. 117–142. Emerald Group, London. doi:10.1108/S1529-212620160000022016

Cowling, R., Egoh, B., Knight, A., O'Farrell, P., Reyers, B., Rouget, M., Roux, D., Welz, A. & Wilhelm-Rechman, A. (2008) An operational model for mainstreaming ecosystem services for implementation. *PANAS*, **105**, 9483–9488.

Daron, J.D., Sutherland, K., Jack, C. & Hewitson, B. (2015) The role of regional climate projections in managing complex socio-ecological systems. *Regional Environmental Change*, **15**, 1–12. doi.org/10.1007/s10113-014-0631-y

De Anguita, P.M. & Wagner, J.E. (2010) *Environmental social accounting matrices: theory and applications*. Routledge, New York.

De Leon, A., Leonhard, S. & Martius, C. (2016) *More holistic approaches to agriculture needed — an analysis of submissions to SBSTA 44 on agriculture and adaption*. CIFOR brief no. 38. Center for International Forestry Research, Bogor, Indonesia.

Denier, L., Scherr, S., Shames, S., Chatterton, P., Hovani, L. & Stam, N. (2015) The little sustainable landscapes book. Global Canopy Programme, Oxford, UK.

Duffy, R. & Humphreys, J. (2017) Poaching, wildlife trafficking and human security. *Poaching, wildlife trafficking and security in Africa* (ed. by C. Haenlein & M. Smith), pp. 22–38. Routledge, London.

Fabricius, C., Koch, E., Turner, H. & Sisitka, L. (2013) What we have learnt from a decade of experimentation. *Rights, resources & rural development — Community-based natural resource management in Southern Africa* (ed. by K. Fabricius & T. Magome), pp. 271–281. Earthscan, London.

FAO (2014) Agroecology for Food Security and Nutrition. *Proceedings of the FAO International Symposium,* 18-19 September 2014, Rome, Italy.

FAO (2017) *Unasylva,* **68**, 27–39.

Foli, A., Ros-Tonen, M., Reed, J., Sunderland, T. (2017) Natural resource management schemes as entry points for integrated landscape approaches: evidence from Ghana and Burkina Faso. *Environmental Management,* **59**, 1-16. doi:10.1007/s00267-017-0866-8

Frost, P., Campbell, B., Medina, G. & Usongo, L. (2006) Landscape-scale approaches for integrated natural resource management in tropical forest landscapes. *Ecology and Society*, **11**, 30.

Fynn, R., David, A., Peel, M. & Garine-Wichatitsky, M. (2016) Strategic management of livestock to improve biodiversity conservation in African savannahs: a conceptual basis for wildlife–livestock coexistence. *Journal of Applied Ecology*, **53**, 388-397. doi:10.1111/1365-2664.12591

Gronau, S., Winter, E. & Grote, U. (2017) Modelling nature-based tourism impacts on rural development and conservation in Sikunga Conservancy, Namibia. *Development Southern Africa*, **34**, 276–294, doi:10.1080/0376835X.2016.1269638.

Gupta, C. (2013) Elephants, safety nets and agrarian culture: understanding human-wildlife conflict and rural livelihoods around Chobe National Park, Botswana. *Journal of Political Ecology*, 20, 238–254.

Humavindu, M. & Stage, J. (2015) Community-based wildlife management failing to link conservation and financial viability. *Animal Conservation*, **20**, 3-14.

Khumalo K. & Yung, L. (2015) Women, human-wildlife conflict, and CBNRM: hidden impacts and vulnerabilities in Kwandu Conservancy, Namibia. *Conservation and Society*, **13**, 232–243.

Koch, C. (2017) *Simulation of an investment in an agroforestry system with* Faidherbia albida *in the Zambezi Region of Namibia*. Bachelor's thesis, Leibniz Universität, Hannover.

Kolding, J., van Zwieten, P., Marttin, F. & Poulain, F. (2016a) *Fisheries in the drylands of sub-Saharan Africa — 'Fish come with the rains'. Building resilience for fisheries-dependent livelihoods to enhance food security and nutrition in the drylands.* FAO Fisheries and Aquaculture Circular No. 1118. FAO, Rome.

Kolding, J., van Zwieten, P., Mosepele, M. (2016b) 'Where there is water there is fish' — Small-scale inland fisheries in Africa: dynamics and importance. *A history of water, series 3, volume 3. Water and food: from hunter-gatherers to global production in Africa* (ed. by T. Tvedt & T. Oestigaard), pp 1-18. I.B. Tauris, London.

Kozar, R., Buck, L., Barrow, E., Sunderland, T., Catacun, D., Planicka, C., Hart, A. & Willemen, L. (2014) *Towards viable landscape governance systems: what works?* EcoAgriculture Partners, Washington DC.

Kuyah, S., Öborn, I., Jonsson, M., Dahlin A.S., Barrios, E., Muthuri, C., Malmer, A., Nyaga, J., Magaju, C., Namirembe, S., Nyberg, Y. & Sinclair, F.L. (2016) Trees in agricultural landscapes enhance provision of ecosystem services in Sub-Saharan Africa. *International Journal of Biodiversity Science, Ecosystem Services & Management,* **12**, 255–273. doi:10.1080/21513732.2016.1214178

Mallet, P., Maireles, M., Kennedy, E. & Devisscher, M. (2016) ISEAL report: how sustainability standards can contribute to landscape approaches and zero deforestation commitments. ISEAL Alliance, London.

Masso, C., Baijukya, F., Ebanyat, P., Bouaziz, S., Wendt, J., Bekunda, M. & Vanlauwe, B. (2017) Dilemma of nitrogen management for future food security in sub-Saharan Africa — a review. *Soil Research*, **55**, 425–434. doi:10.1071/SR16332

Mendelsohn, J. (2010) Atlas of Namibia: a portrait of the land and its people. Sunbird, Cape Town, South Africa.

Moritz, M., Hamilton, I., Yoak, A., Scholtee, P., Cronley, J., Maddocka, P. & Hongyang Pi, H. (2015) Simple movement rules result in ideal free distribution of mobile pastoralists. *Ecological Modelling*, **305**, 54–63.

Morton, H., Winter, E. & Grote, U. (2016) Assessing natural resource management through integrated environmental and social-economic accounting: the case of a Namibian conservancy. *Journal of Environment and Development*, **25**, 396–425.

Mosimane, A. & Silva, J. (2015) Local governance institutions, CBNRM, and benefit-sharing systems in Namibian conservancies. *Journal of Sustainable Development*, **8**, 99–112.

Naidoo, R, Weaver, LC, Diggle, RW, Matongo, G, Stuart-Hill, G & Thouless, C (2016) Complementary benefits of tourism and hunting to communal conservancies in Namibia. *Conservation Biology,* **30**, 628–38.

Nyirenda, V., Kaoma, C., Nyirongo, S., Lwali, C. & Chomba, C. (2017) Social exchange and structuralist-constructivism approaches for enhanced ecotourism and food security in wildlife-agrarian mosaic landscapes: insights from eastern Zambia. *International Journal of Tourism Policy*, **7,** 93-109. doi:10.1504/IJTP.2017.085293

Oborn, I., Vanlauwe, B., Phillips, Thomas, R., Brooijmans, W. & Atta-Krah, K. (2017) *Sustainable intensification in smallholder agriculture*. Routledge, London.

Ostrom, E. (2012) Nested externalities and polycentric institutions: must we wait for global solutions to climate change before taking actions at other scales? *Economic Theory*, **49**, 353–369.

Ostrom, E. (2013) Polycentric systems: multi-level governance involving a diversity of organizations. *Global environmental commons* (ed. by E. Brousseau, T. Dedeurwaerdere, P. Jouvet, & M. Willinger), pp. 105–126. Oxford University Press, Oxford, UK.

Perrotton, A., de Garine-Wichatitsky, M., Valls-Fox, H. & Le Page, C. (2017) My cattle and your park: codesigning a role-playing game with rural communities to promote multistakeholder dialogue at the edge of protected areas. *Ecology and Society*, **22**, 35. doi:10.5751/ES-08962-220135

PON (2017). Program on Negotiation. Harvard Law School. https://www.pon.harvard.edu

Purnomo, H., Guizol, P. & Mendoza, G. (2009). Exploring partnerships between local communities and timber companies: an experiment using the role-playing games approach. *International Journal of Forestry Research,* **2009**, 451362. doi:10.1155/2009/451362

Reed, J., van Vianen, J., Deakin, E., Barlow, J. & Sunderland, T. (2016) Integrated landscape approaches to managing social and environmental issues in the tropics: learning from the past to guide the future. *Global Change Biology*, **22**, 2540–2554. doi:10.1111/gcb.13284.

Röttgers, D. (2016) Conditional cooperation, context and why strong rules work — a Namibian common-pool resource experiment. *Ecological Economics*, **129**, 21–31.

Rumore, D., Schenk, T. & Susskind, L. (2016) Role-play simulations for climate change adaptation, education and engagement. *Nature Climate Change,* **6**, 745–750. doi:10.1038/nclimate3084.

Salvini, G., van Paassen, A., Lightenberg, A., Carrero, G. & Bregt, A. (2016) A role-playing game as a tool to facilitate social learning and collective action towards climate smart agriculture: lessons learned from Apuí, Brazil. *Environmental Science & Policy,* **63**, 113–121.

Food security

Sayer J., Sunderland T., Ghazoul J., Pfund, J.-L., Sheilb, D., Meijaard, E., Ventera, M., Klintuni, A., Dayb, M., van Oostenj, C. & Buckk, L. (2013) Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. *Proceedings of the National Academy of Sciences of the United States of America*, **110**, 8349–8356.

Schlüter, M., Baeza, A., Dressler, G., Frank, K., Groeneveld, J., Jager, W., Janssen, M., McAllister, R., Müller, B., Orach, K., Schwarz, N. & Wijermans, N. (2017) A framework for mapping and comparing behavioural theories in models of social-ecological systems. *Ecological Economics,* **131**, 21–35.

Scholz, G., Dewulf, A. & Pahl-Wostl, C. (2014) An analytical framework of social learning facilitated by participatory methods. *Systemic Practice and Action Research*, **27**, 575–591. https://doi.org/10.1007/s11213-013-9310-z

Silva, J. & Mosimane, A. (2012) Conservation-based rural development in Namibia: a mixed-methods assessment of economic benefits. *The Journal of Environment and Development,* **22**, 25–50.

Snapp, S. & Pound, B. (2017) Agricultural systems: agroecology and rural innovation for development: agroecology and rural innovation for development. Academic Press Elsevier, London.

Speelman, E.N., García-Barrios, L.E., Groot, J.C.J. & Tittonell, P. (2014) Gaming for smallholder participation in the design of more sustainable agricultural landscapes. Agricultural Systems, **126**, 62–75.

Tittonell, P. (2014) Ecological intensification of agriculture — sustainable by nature. *Current Opinion in Environmental Sustainability*, **8**, 53–61.

Tweddle, D., Cowx, I.G., Peel, R.A. & Weyl, O.L.F. (2015) Challenges in fisheries management in the Zambezi, one of the great rivers of Africa. *Fisheries Management and Ecology*, **22**, 99–111.

Tweddle, D., Peel, R.A., Taylor, G.F., Murphy, C. & Weyl, O.L.F (2018) Management of Zambezian fisheries, with particular emphasis on Lake Liambezi, based on sound scientific and social research. This volume.

UNSTAT. (2016) SEEA experimental ecosystem accounting. http://unstats.un.org/unsd/envaccounting/eea_project/default.asp

Van der Duim, V., Lamers, M. & van Wijk, J. (2015) *Institutional arrangements for conservation, development and tourism in eastern and southern Africa: a dynamic perspective.* Springer, Dordrecht.

Villamore, G., van Noordwijk, M., Djanibekov, U., Chiong-Javier, M. & Catacutan, D. (2014) Gender differences in land-use decisions: shaping multifunctional landscapes? *Current Opinion in Environmental Sustainability*, **6**, 128–133.

Winter, E., Morton, H. & Röttgers, D. (2017) Handbook of social learning and economic field experiments. Leibniz Universität, Hannover.

References [CrossRef]

Allen, C.R. & Garmestani, A.S. (2015) Adaptive management. *Adaptive management of social–ecological systems* (ed. by C.R. Allen & A.S. Garmestani), pp. 1–10. Springer, Dordrecht, The Netherlands. CrossRef

Altieri, M., Funes-Monzote, F. & Petersen, P. (2012) Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. *Agronomy for Sustainable Development*, **32**, 1–13. CrossRef

Anderies, J.M., Janssen, M.A., Bousquet, F., Cardenas, J.C., Castillo, D., Lopez, M.-C., Tobias, R., Vollan, B. & Wutich, A. (2011) The challenge of understanding decisions in experimental studies of common pool resource governance. *Ecological Economics*, **70**, 1571–1579. CrossRef

Angelsen, A., Jagger, P., Babigumira, R., Belcher, B., Hogarth, N. J., Bauch, S. & Wunder, S. (2014) Environmental income and rural livelihoods: a global comparative analysis. *World Development*, **64(Suppl 1)**, S12–S28. CrossRef

Barendse, J., Roux, D., Currie, B., Wilson, N. & Fabricius, C. (2016) A broader view of stewardship to achieve conservation and sustainability goals in South Africa. *South African Journal of Science*, **112**, 15. CrossRef

Brown, C., Ravallion, M. & van de Walle, D. (2017) *Most of Africa's nutritionally vulnerable women and children are not found in poor households.* Guide Working Paper Series no. 2. Georgetown University Initiative on Innovation, Development and Evaluation, Washington, DC. https://gui2de.georgetown.edu

Burroway, R. (2016) Empowering women, strengthening children: a multi-level analysis of gender inequality and child malnutrition in developing countries. *Gender and food: from production to consumption and after* (ed. by M.T. Segal & V. Demos), pp. 117–142. Emerald Group, London. CrossRef

Cowling, R., Egoh, B., Knight, A., O'Farrell, P., Reyers, B., Rouget, M., Roux, D., Welz, A. & Wilhelm-Rechman, A. (2008) An operational model for mainstreaming ecosystem services for implementation. *PANAS*, **105**, 9483–9488. CrossRef

Daron, J.D., Sutherland, K., Jack, C. & Hewitson, B. (2015) The role of regional climate projections in managing complex socio-ecological systems. *Regional Environmental Change*, **15**, 1–12. CrossRef

De Anguita, P.M. & Wagner, J.E. (2010) *Environmental social accounting matrices: theory and applications*. Routledge, New York.

De Leon, A., Leonhard, S. & Martius, C. (2016) *More holistic approaches to agriculture needed — an analysis of submissions to SBSTA 44 on agriculture and adaption*. CIFOR brief no. 38. Center for International Forestry Research, Bogor, Indonesia.

Denier, L., Scherr, S., Shames, S., Chatterton, P., Hovani, L. & Stam, N. (2015) The little sustainable landscapes book. Global Canopy Programme, Oxford, UK.

Duffy, R. & Humphreys, J. (2017) Poaching, wildlife trafficking and human security. *Poaching, wildlife trafficking and security in Africa* (ed. by C. Haenlein & M. Smith), pp. 22–38. Routledge, London.

Fabricius, C., Koch, E., Turner, H. & Sisitka, L. (2013) What we have learnt from a decade of experimentation. *Rights, resources & rural development — Community-based natural resource management in Southern Africa* (ed. by K. Fabricius & T. Magome), pp. 271–281. Earthscan, London.

FAO (2014) Agroecology for Food Security and Nutrition. *Proceedings of the FAO International Symposium*, 18-19 September 2014, Rome, Italy.

FAO (2017) *Unasylva*, **68**, 27–39.

Foli, A., Ros-Tonen, M., Reed, J., Sunderland, T. (2017) Natural resource management schemes as entry points for integrated landscape approaches: evidence from Ghana and Burkina Faso. *Environmental Management*, **59**, 1-16. CrossRef

Frost, P., Campbell, B., Medina, G. & Usongo, L. (2006) Landscape-scale approaches for integrated natural resource management in tropical forest landscapes. *Ecology and Society*, **11**, 30. CrossRef

Fynn, R., David, A., Peel, M. & Garine-Wichatitsky, M. (2016) Strategic management of livestock to improve biodiversity conservation in African savannahs: a conceptual basis for wildlife–livestock coexistence. *Journal of Applied Ecology*, **53**, 388-397. CrossRef

Gronau, S., Winter, E. & Grote, U. (2017) Modelling nature-based tourism impacts on rural development and conservation in Sikunga Conservancy, Namibia. *Development Southern Africa*, **34**, 276–294. CrossRef

Gupta, C. (2013) Elephants, safety nets and agrarian culture: understanding human-wildlife conflict and rural livelihoods around Chobe National Park, Botswana. *Journal of Political Ecology*, 20, 238–254. CrossRef

Humavindu, M. & Stage, J. (2015) Community-based wildlife management failing to link

conservation and financial viability. *Animal Conservation*, **20**, 3-14. CrossRef

Khumalo K. & Yung, L. (2015) Women, human-wildlife conflict, and CBNRM: hidden impacts and vulnerabilities in Kwandu Conservancy, Namibia. *Conservation and Society*, **13**, 232–243. CrossRef

Koch, C. (2017) *Simulation of an investment in an agroforestry system with* Faidherbia albida *in the Zambezi Region of Namibia*. Bachelor's thesis, Leibniz Universität, Hannover.

Kolding, J., van Zwieten, P., Marttin, F. & Poulain, F. (2016a) *Fisheries in the drylands of sub-Saharan Africa — 'Fish come with the rains'. Building resilience for fisheries-dependent livelihoods to enhance food security and nutrition in the drylands.* FAO Fisheries and Aquaculture Circular No. 1118. FAO, Rome.

Kolding, J., van Zwieten, P., Mosepele, M. (2016b) 'Where there is water there is fish' — Small-scale inland fisheries in Africa: dynamics and importance. *A history of water, series 3, volume 3. Water and food: from hunter-gatherers to global production in Africa* (ed. by T. Tvedt & T. Oestigaard), pp 1-18. I.B. Tauris, London.

Kozar, R., Buck, L., Barrow, E., Sunderland, T., Catacun, D., Planicka, C., Hart, A. & Willemen, L. (2014) *Towards viable landscape governance systems: what works?* EcoAgriculture Partners, Washington DC.

Kuyah, S., Öborn, I., Jonsson, M., Dahlin A.S., Barrios, E., Muthuri, C., Malmer, A., Nyaga, J., Magaju, C., Namirembe, S., Nyberg, Y. & Sinclair, F.L. (2016) Trees in agricultural landscapes enhance provision of ecosystem services in Sub-Saharan Africa. *International Journal of Biodiversity Science, Ecosystem Services & Management*, **12**, 255–273. CrossRef

Mallet, P., Maireles, M., Kennedy, E. & Devisscher, M. (2016) ISEAL report: how sustainability standards can contribute to landscape approaches and zero deforestation commitments. ISEAL Alliance, London.

Masso, C., Baijukya, F., Ebanyat, P., Bouaziz, S., Wendt, J., Bekunda, M. & Vanlauwe, B. (2017) Dilemma of nitrogen management for future food security in sub-Saharan Africa — a review. *Soil Research*, **55**, 425–434. CrossRef

Mendelsohn, J. (2010) Atlas of Namibia: a portrait of the land and its people. Sunbird, Cape Town, South Africa.

Moritz, M., Hamilton, I., Yoak, A., Scholtee, P., Cronley, J., Maddocka, P. & Hongyang Pi, H. (2015) Simple movement rules result in ideal free distribution of mobile pastoralists. *Ecological Modelling*, **305**, 54–63. CrossRef

Morton, H., Winter, E. & Grote, U. (2016) Assessing natural resource management through integrated environmental and social-economic accounting: the case of a Namibian conservancy. *Journal of Environment and Development*, **25**, 396–425. CrossRef

Mosimane, A. & Silva, J. (2015) Local governance institutions, CBNRM, and benefit-sharing systems in Namibian conservancies. *Journal of Sustainable Development*, **8**, 99–112. CrossRef

Naidoo, R, Weaver, LC, Diggle, RW, Matongo, G, Stuart-Hill, G & Thouless, C (2016) Complementary benefits of tourism

and hunting to communal conservancies in Namibia. CrossRef
Conservation Biology, **30**, 628–38.
Nyirenda, V., Kaoma, C., Nyirongo, S., Lwali, C. & Chomba, C. (2017) Social exchange and structuralist-constructivism approaches for enhanced ecotourism and food security in wildlife-agrarian mosaic landscapes: insights from eastern Zambia. *International Journal of Tourism Policy*, **7,** 93-109. CrossRef
Oborn, I., Vanlauwe, B., Phillips, Thomas, R., Brooijmans, W. & Atta-Krah, K. (2017) *Sustainable intensification in smallholder agriculture*. Routledge, London.
Ostrom, E. (2012) Nested externalities and polycentric institutions: must we wait for global solutions to climate change before taking actions at other scales? *Economic Theory*, **49**, 353–369. CrossRef
Ostrom, E. (2013) Polycentric systems: multilevel governance involving a diversity of organizations. *Global environmental commons* (ed. by E. Brousseau, T. Dedeurwaerdere, P. Jouvet, & M. Willinger), pp. 105–126. Oxford University Press, Oxford, UK.
Perrotton, A., de Garine-Wichatitsky, M., Valls-Fox, H. & Le Page, C. (2017) My cattle and your park: codesigning a role-playing game with rural communities to promote multistakeholder dialogue at the edge of protected areas. *Ecology and Society*, **22**, 35. CrossRef
PON (2017). Program on Negotiation. Harvard Law School. https://www.pon.harvard.edu
Purnomo, H., Guizol, P. & Mendoza, G. (2009). Exploring partnerships between local communities and timber companies: an experiment using the role-playing games approach. *International Journal of Forestry Research*, **2009**, 451362. CrossRef
Reed, J., van Vianen, J., Deakin, E., Barlow, J. & Sunderland, T. (2016) Integrated landscape approaches to managing social and environmental issues in the tropics: learning from the past to guide the future. *Global Change Biology*, **22**, 2540–2554. CrossRefdoi:10.1111/gcb.13284.
Röttgers, D. (2016) Conditional cooperation, context and why strong rules work — a Namibian common-pool resource experiment. *Ecological Economics*, **129**, 21–31. CrossRef
Rumore, D., Schenk, T. & Susskind, L. (2016) Role-play simulations for climate change adaptation, education and engagement. *Nature Climate Change*, **6**, 745–750. CrossRef
Salvini, G., van Paassen, A., Lightenberg, A., Carrero, G. & Bregt, A. (2016) A role-playing game as a tool to facilitate social learning and collective action towards climate smart agriculture: lessons learned from Apuí, Brazil. *Environmental Science & Policy*, **63**, 113–121. CrossRef
Sayer J., Sunderland T., Ghazoul J., Pfund, J.-L., Sheilb, D., Meijaard, E., Ventera, M., Klintuni, A., Dayb, M., van Oostenj, C. & Buckk, L. (2013) Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. *Proceedings of the National Academy of Sciences of the United States of America*, **110**, 8349–8356. CrossRef
Schlüter, M., Baeza, A., Dressler, G., Frank, K., Groeneveld, J., Jager, W., Janssen, M., McAllister, R., Müller, B., Orach, K., Schwarz, N. & Wijermans, N. (2017) A framework for mapping and comparing behavioural theories in models of social-ecological systems. *Ecological Economics*, **131**, 21–35. CrossRef
Scholz, G., Dewulf, A. & Pahl-Wostl, C. (2014) An analytical framework of social learning facilitated by participatory methods. *Systemic Practice and Action Research*, **27**, 575–591. CrossRef
Silva, J. & Mosimane, A. (2012) Conservation-based rural development in Namibia: a mixed-methods assessment of economic benefits. *The Journal of Environment and Development*, **22**, 25–50. CrossRef
Snapp, S. & Pound, B. (2017) Agricultural systems: agroecology and rural innovation for development: agroecology and rural innovation for development. Academic Press Elsevier, London.
Speelman, E.N., García-Barrios, L.E., Groot, J.C.J. & Tittonell, P. (2014) Gaming for smallholder participation in the design of more sustainable agricultural landscapes. *Agricultural Systems*, **126**, 62–75. CrossRef
Tittonell, P. (2014) Ecological intensification of agriculture — sustainable by nature. *Current Opinion in Environmental Sustainability*, **8**, 53–61. CrossRef
Tweddle, D., Cowx, I.G., Peel, R.A. & Weyl, O.L.F. (2015) Challenges in fisheries management in the Zambezi, one of the great rivers of Africa. *Fisheries Management and Ecology*, **22**, 99–111. CrossRef
Tweddle, D., Peel, R.A., Taylor, G.F., Murphy, C. & Weyl, O.L.F (2018) Management of Zambezian fisheries, with particular emphasis on Lake Liambezi, based on sound scientific and social research. This volume. CrossRef
UNSTAT. (2016) SEEA experimental ecosystem accounting. http://unstats.un.org/unsd/envaccounting/eea_project/default.asp
Van der Duim, V., Lamers, M. & van Wijk, J. (2015) *Institutional arrangements for conservation, development and tourism in eastern and southern Africa: a dynamic perspective*. Springer, Dordrecht.
Villamore, G., van Noordwijk, M., Djanibekov, U., Chiong-Javier, M. & Catacutan, D. (2014) Gender differences in land-use decisions: shaping multifunctional landscapes? *Current Opinion in Environmental Sustainability*, **6**, 128–133. CrossRef
Winter, E., Morton, H. & Röttgers, D. (2017) Handbook of social learning and economic field experiments. Leibniz Universität, Hannover.

Woodland resources and management in southern Africa

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Abstract: The countries of southern Africa have an average forest cover of 32% with most forest situated in the tropics. These dry to moist forests are deciduous with a few evergreen species. The open canopy allows enough light to reach the ground to allow the development of a rich grass layer. Generally, these forests are referred to as woodlands. The article gives an overview of the Miombo, *Baikiaea* and Mopane woodlands of Angola, Zambia, Namibia, and Botswana and focuses on their composition, wood and non-wood resources. Plantation forestry is briefly discussed with most information from South Africa, which has the largest commercial forestry sector in the region. Threats to the southern African woodlands are highlighted, and the current status of woodland monitoring and management is summarised.

Resumo: Os países da África Austral têm uma cobertura florestal média de 32%, com a maioria das florestas situadas nos trópicos. Estas florestas secas ou húmidas são decíduas, com algumas espécies de folha perene. A copa aberta permite que luz suficiente chegue ao solo para permitir o desenvolvimento de uma camada rica de herbáceas. No geral, estas florestas são referidas como matas. O artigo apresenta uma visão geral das matas de Miombo, *Baikiaea* e Mopane de Angola, Zâmbia, Namíbia e Botswana, concentrando-se na sua composição e recursos lenhosos e não-lenhosos. A plantação florestal é brevemente discutida, com a maior parte da informação proveniente da África do Sul, a qual tem a maior indústria comercial de exploração florestal na região. São destacadas as ameaças às matas da África Austral e é resumido o estado actual de monitorização e gestão das matas.

Introduction

Southern Africa has about 190 million ha of forests with an average of 32% forest cover. Forest types range from tropical moist and rainforest in the north to subtropical dry and humid forest, as well as mountain forest, in the south (Fig. 1). Most vegetation classified by FAO as tropical forest is commonly named "woodland" in the region, for example Miombo or Mopane woodland (Timberlake & Chidumayo, 2011; Chirwa et al., 2014). Woodlands differ from forests because of their more open canopy cover and the characteristic presence of grasses in the understorey (Putz & Redford, 2010; Ratnam et al., 2011; Oliveras & Malhi, 2016). Tropical woodlands are dominated by C4 grasses. The C4 photosynthetic pathway makes them tolerant to higher temperatures and drought but less tolerant to shade compared to C3 grasses (Ratnam et al., 2011; Oliveras & Malhi, 2016). We will use the term "woodland" in this article to follow regional convention and to highlight that tropical rainforests and Afromontane forests are not discussed here. For information on the dense mountain, coastal and mist forests of South Africa, we refer to other studies (e.g. Mensah et al., 2017b, 2017a; Ngubeni, 2015; Seifert et al., 2014; Vermeulen, 2009). The term "forest" is, however, retained when referring to data from FAO's forest resources assessments and collected through remote sensing, as they are based on the FAO definition for forest which specifies a minimum canopy cover of 10% (FAO, 2012). There is no internationally accepted definition for woodland (Putz and Redford, 2010) and we define it as vegetation characterised by trees – woody plants able to reach a minimum height of 5 m (FAO, 2012) – with tree crown cover between 10%

(FAO, 2012) and 60% (Hirota et al., 2011; Kutsch et al., 2011), and an understory where C4 grasses are present.

The largest extent of forest and woodland is found in the northern areas of southern Africa, which receive a higher amount of precipitation, such as Angola and Zambia (Tab. 1). Namibia, Botswana and South Africa, with their predominantly semi-arid climate, have a relatively small forest area. This article focuses on the woodland resources of southern Angola, western Zambia, northern Namibia, and northern Botswana, where most SASSCAL projects took place (Fig. 1). Plantation forestry in the SASSCAL countries is briefly discussed with most information originating from South Africa, which has the largest commercial forestry industry in the region.

Woodland composition

Most of Zambia and Angola are characterised by Miombo woodlands (Fig. 1). In southern Angola and south-western Zambia, woody species diversity gradually declines and Miombo is replaced by more open and drier Mopane and *Baikiaea* woodlands (FAO, 2000; Scholes et al., 2002; Timberlake & Chidumayo, 2011). Further south, in Namibia and Botswana, the canopy cover of the *Baikiaea* woodlands decreases, progressively more species of the legume subfamily Caesalpinioideae (formerly Mimosoideae) appear, and the open woodlands gradually

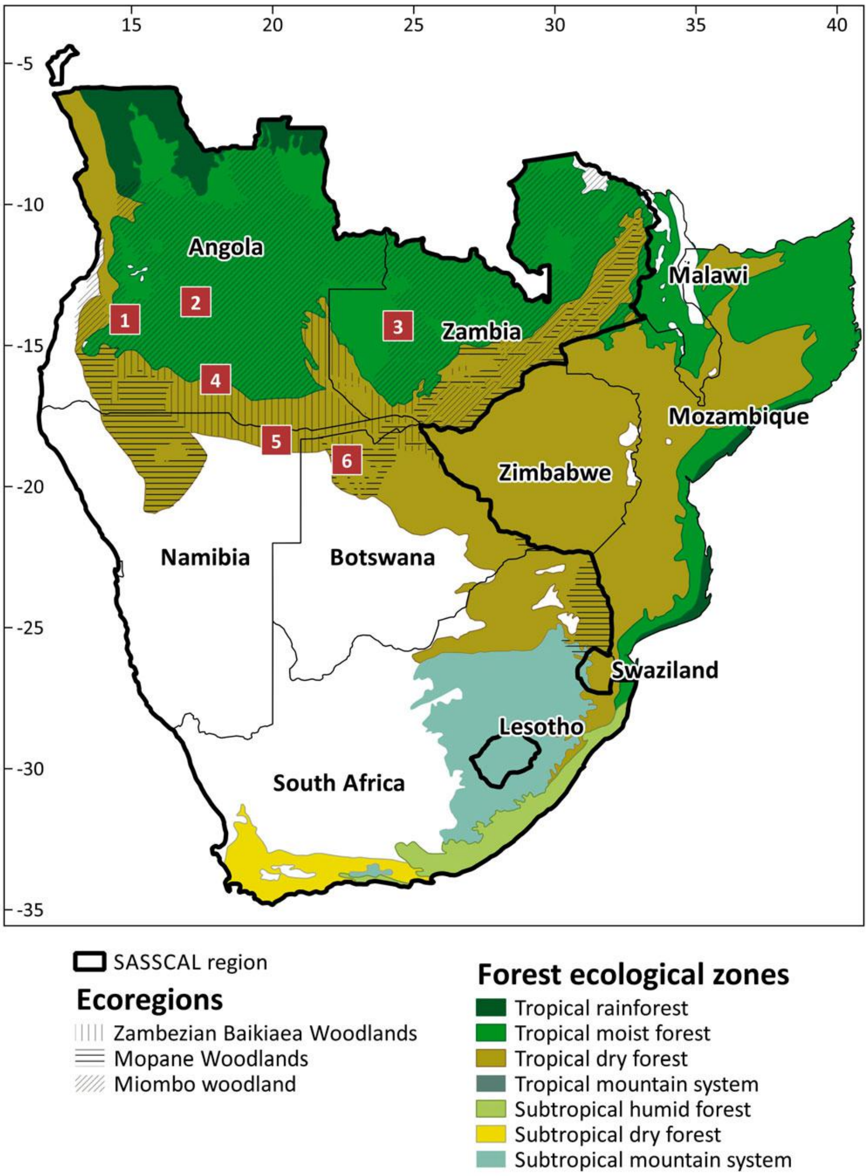

Figure 1: Forest ecological zones in the SASSCAL countries according to FAO (2000) with indication of ecoregions according to WWF (Olson et al., 2001). The numbers 1 to 6 indicate the locations of the forest inventories summarised in Table 2: 1. Huíla, 2. Bié, 3. Western Province, 4. Cuando Cubango, 5. Kavango's, and 6. North-West Province.

Table 1: Area of forest and forest loss in southern Africa and the SASSCAL countries based on FAO (2015) and (in grey) Hansen et al. (2013) with forest including woodland.

Country	Land area (1000 ha)	Forest area with canopy cover >= 10% (1000 ha)	Forest cover (% of land area)	Forest area with canopy cover >= 25% (1000 ha)	Planted forest area (1000 ha)	Forest loss 2000 – 2015 (1000 ha)	Forest loss within forest area 2000 – 2015 (%)	Forest loss 2000 – 2012 (1000 ha)	Forest gain 2000 – 2012 (1000 ha)
SASSCAL									
Angola	124670	57856	46	63357	125	1872	3.2	1932	64
Botswana	56673	10840	19	54	0	1695	15.6	6	0
Namibia	82329	6919	8	13	0	1113	16.1	13	0
South Africa	121447	9241	8	7125	1763	0	0.0	953	831
Zambia	74339	48635	65	31616	64	2499	5.1	1316	18
SASSCAL total	**459458**	**133491**	**29**	**102164**	**1952**	**7179**	**5.4**	**4219**	**913**
Other southern African									
Lesotho	3035	49	2	12	17	-7	-14.3	0	0
Malawi	9428	3147	33	2216	419	420	13.3	129	10
Mozambique	78638	37940	48	37141	75	3248	8.6	2155	145
Swaziland	1720	586	34	595	135	-68	-11.6	75	60
Zimbabwe	38685	14062	36	2411	87	4832	34.4	387	49
Other total	**131506**	**55784**	**42**	**42373**	**733**	**8425**	**15.1**	**2746**	**264**
Southern Africa TOTAL	**590964**	**189275**	**32**	**144537**	**2685**	**15604**	**8.2**	**6965**	**1177**

Figure 2: Miombo in the Serenje National Forest, Central Province, Zambia, at the end of the rainy season. The road connects a larger illegal settlement within the woodland with Zambia's Great North Road (Photo: D. Parduhn).

change into semi-arid scrublands (Burke, 2002; Scholes et al., 2002; Chirwa et al., 2014). In southern Botswana and northern South Africa, Mopane and Combretaceae woodlands are found south of approximately 19° S (Timberlake & Chidumayo, 2011; Chirwa et al., 2014). The woodlands form part of the revised Miombo ecoregion, an extension of White's Zambezian regional centre of endemism that is characterised by semi-deciduous woodland composed of trees of the legume subfamily Detarioideae (previously Caesalpinioideae) (Timberlake & Chidumayo, 2011; LPWG, 2017). The following sections give more details about the species and structural composition of the different woodland types, except for the Combretaceae woodlands where no SASSCAL activities took place and for which we refer to the work of Shackleton and Scholes (2011), amongst others. Basal area (BA) is used as a proxy for wood volume and biomass; it is the sum of the cross-sectional areas of tree stems at DBH (diameter at breast height, or 1.3 m) in a stand.

Miombo woodland

Miombo sensu stricto, or true Miombo (Fig. 2), is a woodland characterised by three genera of the Detarioideae (formerly Caesalpinioideae): *Brachystegia*, *Julbernardia* and, to a lesser extent, *Isoberlinia* (Timberlake & Chidumayo, 2011; Chirwa et al., 2014). There are two types of Miombo: wet Miombo (annual rainfall > 1000 mm, canopy height > 15 m), and dry Miombo (rainfall < 1000 mm, canopy height < 15 m) (White, 1983; Frost, 1996). Many authors (e.g. Chirwa et al., 2014; Frost, 2000) cite the work of White (1983) to indicate that *Brachystegia boehmi, Brachystegia spiciformis* and *Julbernardia globiflora* are the dominant trees in dry Miombo woodlands. However, in the dry Miombo of southern Angola, *Julbernardia paniculata* and *Brachystegia bakeriana* are the only species of the Miombo genera and they reach their southern limit at a latitude of approximately 16° S (Revermann et al., in press; Baptista, 2014).

SASSCAL forest inventories were performed in Miombo areas of similar mean annual rainfall (950–1100 mm) and thus at the border of dry and wet Miombo. They show that stem density, maximum DBH, and BA increased from western Angola to western Zambia, with the BA in Huíla only half of that recorded in Bié (Tab. 2). The study area in Huíla is the most populated, with approximately 58 persons per km^2 compared to less than 6 persons per km^2 for the other five study areas (Linard et al., 2012). Its low BA is, amongst other reasons, the result of human interventions. The most common species in the Angolan Miombo areas were *J. paniculata* and *B. spiciformis*, which in combination contributed to 36% and 45% of the BA in Bié and Huíla, respectively. In Huíla, *Brachystegia longifolia* was another important canopy tree, representing 13% of both stems and BA. In Bié, *Erythrophleum africanum* was as common as the two aforementioned species, contributing 14% of the total BA. Important timber species such

Table 2: Structural composition of typical woodland types in the SASSCAL region based on forest inventory data for trees with minimum diameter at breast height (DBH) of 10 cm. Only living trees were measured. Multiple stems were measured except for location 6. The location numbers are indicated in Figure 1.

Location number	**1**	**2**	**3**	**4**	**5**	**6**
Forest type	**Miombo**	**Miombo**	**Miombo**	***Baikiaea***	***Baikiaea***	**Mopane**
Country	Angola	Angola	Zambia	Angola	Namibia	Botswana
Province/Region	Huíla	Bie	Western	Cuando Cubango	Kavango W/E	North-West
Mean annual rainfall (mm)	1000	1100	950	700	550	450
Number of plots	107	35	60	24	114	15
Stem density (ha^{-1})	277	370	480	87	116	162
Basal area (m^2.ha^{-1})	7.1	11.4	13.9	8.1	5.6	5.2
Mean DBH (cm)	17.9	17.7	18.3	39.3	29.9	18.8
Maximum DBH (cm)	31.1	39.6	44.5	65.3	52.8	39.6
Maximum height (m)		13.6	22.1	12.6	12.0	9.2

as *Pericopsis angolensis* and *Pterocarpus angolensis* had a low occurrence (< 0.6% BA).

In the Zambian Miombo, inventories showed that the most common species recorded were *J. paniculata* and *Brachystegia boehmii*, together contributing 49% of the total BA. Other important canopy species were *Guibourtia coleosperma* (10% BA) and *Cryptosepalum exfoliatum* subsp. *pseudotaxus* (6% BA). Timber species such as *Pericopsis angolensis, Pterocarpus angolensis* and *Burkea africana* are present but not abundant (1–3% BA). Tree height at the Zambian sites reached on average a maximum of 22 m, remarkably high for Miombo woodland with mean annual rainfall of 950 mm, while the BA was much higher than in a study of Chidumayo (1987a) for the same area (7.9 $m^2.ha^{-1}$).

Baikiaea **woodland**

The *Baikiaea* woodlands are characterised by the species *Baikiaea plurijuga* (Fig. 3), an important timber tree whose northern boundary in Angola is at a latitude of 16° S (Baptista, 2014; Revermann et al., 2015). Forest inventories in southern Angola and Namibia (Tab. 2) show, however, that the species is less dominant than in the eastern parts of the *Baikiaea* woodland (Childes & Walker, 1987; Mitlöhner, 1993; De Cauwer et al., 2016). In fact, the contribution of *B. plurijuga* to the total number of stems (3–11%) and total BA (5–14%) is similar to that of the other co-dominant species, *B. africana, Pterocarpus angolensis,* and *Schinziophyton rautanenii,* which contributed up to 18%, 10%, and 34% respectively of the total BA in the *Baikiaea* study areas. Forest inventories over larger areas show that *B. africana* is the most dominant canopy tree (23% BA) in the western *Baikiaea* woodlands, followed by *B. plurijuga* (De Cauwer et al., 2016). Several authors therefore refer to these woodlands as *Burkea* (Frost, 1996; Burke, 2002), Burkeo-Pterocarpetea (Strohbach & Petersen, 2007) or *Baikiaea-Burkea* (Stellmes et al., 2013) woodlands. De Cauwer et al. (2016) argue that *B. africana* is an early succession and non-differentiating species, and

Figure 3: *Baikiaea* woodlands: (a) overview during the growth season and (b) *Baikiaea plurijuga* with one historically felled stem in the Mashare area of Kavango East, northern Namibia (Photos: R. Revermann and V. De Cauwer).

Figure 4: Mopane woodland in the Seronga area, Okavango panhandle, Botswana. *Colophospermum mopane* can be seen in both its (a) shrub form and (b) tree form. (Photos: R. Revermann).

propose the name *Baikiaea-Pterocarpus* woodlands.

E. africanum was still very common at the Angolan *Baikiaea* site with 10% of the total BA, but this decreased to 1% at the Namibian site. Total stem densities and BA in the *Baikiaea* woodlands were much lower than in Miombo, but the average DBH was higher (Tab. 2). BA for the Namibian *Baikiaea* site was also lower than the BA of 8–10 $m^2.ha^{-1}$ in areas with similar rainfall (480–650 mm) of the Combretaceae woodlands (Shackleton & Scholes, 2011), although the latter BA is based on a stem diameter at height 0.05 m instead of DBH.

Mopane woodland

Mopane woodlands are strongly dominated by the species *Colophospermum mopane,* which structurally can occur either as a tree up to 20–25 m tall (Geldenhuys & Golding, 2008) or a shrub (Fig. 4). The distribution range of Mopane woodland (Fig. 1) covers areas with an annual rainfall of 400 to 700 mm (Chirwa et al., 2014) and has distinct boundaries; there is no gradual transformation towards Miombo and *Baikiaea* woodlands. The distribution range of the species *C. mopane* is larger as it includes scrubland, which is not discussed here, and is mainly influenced by frost, minimum temperature, dry season length, and a preference for clay-rich soils (Fraser et al., 1987; Burke, 2006; Stevens et al., 2014). The species represented 79% of all woody species in a forest inventory in Botswana, where it mainly occurs as a small tree (Fig. 4), contributing up to 81% of the BA (Tab. 2). The only other canopy tree species were *B. plurijuga* and *Acacia erioloba* with 11% and 7% of the BA, respectively.

Woodland resources use

Wood for local use

Wood is a major woodland resource for both local and commercial users in the region. Local users mainly collect (dead) firewood, a primary source of domestic energy (Shackleton & Clarke, 2007; Chirwa et al., 2014), and to a lesser extent harvest standing trees for construction purposes. For example, SASSCAL Task 311 showed that villagers living close to the Chobe Forest Reserve in northern Botswana rely heavily on woodland resources, especially firewood from *B. plurijuga*, and earn cash from selling wood as poles. The soft wood of *S. rautanenii,* called Mungongo in Botswana and Manketti in Namibia, is used for dug-out canoes, the main form of transport in the Okavango area, but also as fuel. A study in Cusseque, central Angola, showed that total annual consumption of wood amounted to 484 kg per capita, of which 78% was for firewood and the remainder for house construction (Kissanga Vicente da Silva Firmino, 2016). The most important species used for construction in Cusseque were *Bobgunnia madagascariensis, G. coleosperma,* and *J. paniculata*, the latter also an important tree for fuel, together with *Brachystegia* spp. (Kissanga Vicente da Silva Firmino, 2016). Uses of poles in construction include outside walls, roofs, fences, window frames, furniture, granaries, and coffins. Domestic tools such as hoe and axe handles, pestles and mortars, cooking sticks, and slingshots are also made from local wood. For each purpose, only the most suitable tree type is targeted. The most preferred timber species for local use is *Pterocarpus angolensis,* which has the widest distribution range of all southern African timber trees (De Cauwer et al., 2014). Its wood is regionally referred to as Kiaat (Namibia and South Africa), Mukwa (Zambia) or Girassonde (Angola) (Fig. 5). Kiaat has a medium density (620 kg·m^{-3}), is known for its stability (ITTO, 2017) and is used for the manufacturing of furniture, decking, doors, bowls, and other woodcrafts (Moses, 2013). Other timber species used for construction depend on the area, such as the much harder wood of *Pericopsis angolensis* (Mubanga) in central Zambia, and *B. plurijuga* in southern Zambia (Mukusi), northern Botswana (Mokusi) and northern Namibia (Zambezi teak).

Wood of natural woodlands and plantations for commercial use

Commercial users harvest specific tree species to produce charcoal and timber. Most charcoal is harvested by rural dwellers and then sold in nearby towns or in the regions' capitals, especially in Lusaka and Luanda, where it constitutes the most affordable source of energy (Gumbo et al., 2013, Parduhn & Frantz, 2018). The commercially most important indigenous timber species of the SASSCAL region are *Pterocarpus angolensis, B. plurijuga, G. coleosperma* and *Pterocarpus tinctorius*. SASSCAL Task 035 highlighted the extent of the cross-border trade and showed that at least 15,229 m^3 of Zambian timber and 15,547 m^3 of Angolan timber were exported via Namibia between 2010 and 2014. Trade routes between Namibia, Angola and Zambia were identified, with final markets in South Africa and China (Fig. 6). The most traded wood was that of *Pterocarpus angolensis* (Fig. 5), followed by Zambezi teak (*B. plurijuga*). Only the merchantable logs are traded, which is approximately 28% of the utilisable timber wood volume for Kiaat (Moses, 2013), with the remaining harvested wood being underutilised. Even then, the timber use value of Kiaat, estimated at ZAR 485, for a tree of harvest size, surpasses the carbon value (Moses, 2013).

The wood of *G. coleosperma* is known under the tradename of Rosewood or local names Ushivi (Namibia), Musivi (Angola), and Muzauli (Zambia), and its harvest is on the rise (IRDNC, 2015a). Demand for the wood of *P. tinctorius* (synonym *P. chrysothrix* is used in Zambia), locally named Mukula and known as Padouk outside the SASSCAL region (ITTO, 2017), started fairly recently, driven by the Chinese market. The consequent rates of harvesting and the limited knowledge on the growing stock caused the Zambian government to impose a moratorium on the harvesting and trade of *P. tinctorius* in 2014 (Phiri et al., 2015).

Plantation forestry is much less important than in other regions of the world. The area covered by plantations accounts for about 1.95 million ha in the SASSCAL region, representing only 1.5% of the total forest cover and 0.4% of the total land area (Tab. 1). Comparative values for the European Union and United States of America are 29% and 30% respectively (Forestry South Africa, 2017). Most of the planted forest area in the region, approximately 1.22 million ha, is situated in South Africa (Forestry South Africa, 2017), with the remaining area being in Angola and Zambia (FAO, 2015).

The commercial timber plantations in South Africa account for about 1% of the country's total surface area and mainly consist of exotic species of three genera: *Pinus* (a softwood), and *Eucalyptus* and Australian *Acacia* (both hardwoods). Only 0.3% of the plantation area is based on other species, such as exotic *Quercus* species or the indigenous Yellowwood (*Podocarpus latifolius*) (Forestry South

Figure 5: Wood of *Pterocarpus angolensis*, locally called Kiaat, Mukwa and Girrasonde (Photos: P. Nichol and V. De Cauwer).

Africa, 2016). Most industrial forestry is situated in the high rainfall zones of eastern South Africa, where there is limited scope for expansion because of priority given to other land uses. However, a growing population and an emphasis on renewable, carbon-friendly commodities compel the sector to investigate alternative woodland resources, specifically in dryland situations (du Toit et al., 2018). Most plantations in Angola and Zambia are also based on exotic tree species. SASSCAL

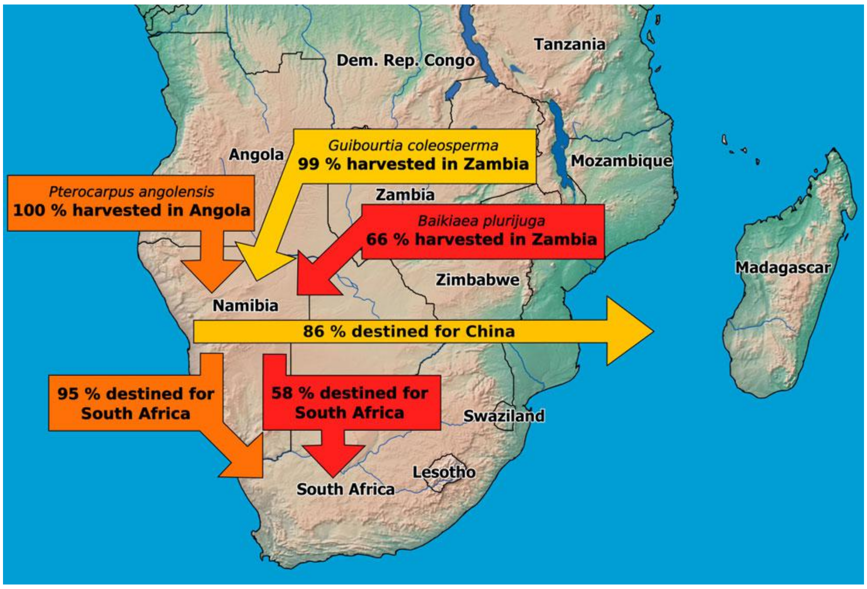

Figure 6: Trade routes of important timber species in south-western Africa (IRDNC, 2015b).

Figure 7: Examples of non-wood forest products: (a) edible caterpillars and (b) mushrooms collected in Zambian Miombo woodland (Photos: D. Parduhn).

Task 037 found that households in the Serenje District of central Zambia start to include timber from pine and eucalypts into their livelihood strategies. A few trial plantations with indigenous species (e.g. Kiaat) were established during colonial times (Groome et al., 1957; Piearce, 1979). The plantations in Angola are mainly composed of *Eucalyptus* species and were either planted during colonial times or very recently. SASSCAL Task 173 trialled the use of *Eucalyptus urograndis*, amongst others, along contour lines to combat erosion in Moxico province, Angola.

Non-wood forest products

A range of fruits, wild vegetables, medicinal and other products are extracted from the region's woodlands, providing an important source of nutrition and cash income (Shackleton & Gumbo, 2010). In the *Baikiaea* woodlands, the fruits of especially *Sclerocarya birrea* (Marula), *G. coleosperma*, *Dialium englerianum, Strychnos* spp. (Monkey orange), and *Grewia* spp. are directly eaten or used to make alcoholic beverages. The seeds of *Bauhinia petersiana* (Mogose) and *S. rautanenii* yield good quality oils. The oil yields for *S. rautanenii* are high (60%) and comparable to those of sunflower and peanut oils (45–55%), indicating their potential for the commercial production of cold-pressed (virgin) oil. *B. petersiana* oil yields are lower (19%) but comparable to those of soybean oil (17–22%) (Yeboah et al., 2017). SASSCAL Task 335 also demonstrated the presence of 73–80% unsaturated fatty acids in *B. petersiana* and *S. rautanenii*, comparable to good quality oils like olive oil, which has about 72% unsaturated fatty acids. The presence of α-eleostearic acid (α-ESA) was also detected in *S. rautanenii* oil. Studies have shown that α-ESA is a tumour suppressing agent and can inhibit breast cancer (Tsuzuki et al., 2004; Grossmann et al., 2009), thus demonstrating the potential suitability of the oil as a health food supplement.

In the Miombo woodlands, rural dwellers harvest bark to make beehives and ropes (preferably from *Brachystegia boehmii* and *Cryptosepalum exfoliatum* subsp. *suffruticans*), and a wide range of edible products. Depending on the season, households collect fruits from trees (e.g. *Uapaca kirkiana*, *Anisophyllea boehmii*, *Parinari curatellifolia*), mushrooms (Fig. 7), roots (e.g. *Rhychosia insignis/munkoyo*), tubers (e.g. chikanda harvested from three orchidioid genera *Disa, Satyrium* and *Habenaria* (Veldman et al., 2017)), as well as wild vegetables (e.g. wild spinach from the *Amaranthus* genus, and *Corchorus olitorius*/Wild okra (Velempini et al., 2003)). They are used for both home consumption and sale, sometimes after processing such as the extraction of oil from *P. curatellifolia* kernels. Honey collected from wild bees is a major source of cash income in the Miombo woodlands (Shackleton & Gumbo, 2010). In contrast to temperate regions, nectar is mainly collected not from herbaceous plants but instead from trees, mainly of the genera *Brachystegia, Julbernardia, Cryptosepalum, Erythrophleum, Bobgunnia*, and *Pterocarpus* (Gröngröft et al., 2015). A small number of households collect a variety of caterpillar species as well as termites. The insect with the highest commercial value in Zambia is an edible caterpillar (Fig. 7) belonging to the moth family Saturniidae, commonly known as Ifishumi (Bemba) and Vinkhubala (Nyanja) (Kachali, unpublished). Bush meat for home consumption is also of importance to most households, with field mice (imbeba) being most popular, followed by cane rats (*Thryonomys* sp./insengele), and wild hares (katili). The roots, bark or leaves of almost all local trees are used for medicinal purposes.

In the Mopane woodlands, *C. mopane* has many economic uses. It provides good quality firewood, construction material, medicines, fodder for game and domestic animals, and young bark for ropes, and it is a food plant for Mopane worms (Madzibane & Potgieter, 1999; Mannheimer & Curtis, 2009). The Mopane worm (*Imbrasia belina*) is the caterpillar of another moth of the Saturniidae, which feeds primarily on the leaves of *C. mopane*. The caterpillars are dried before consumption or sale in both rural and urban centres and provide an important source of protein (61% of dry matter) for the indigenous people (Headings & Rahnema, 2002).

Threats

The rates of deforestation in Africa are lower than in other areas of the tropics. Deforestation is most prevalent in the tropical rainforests, but also in the dense tropical moist and dry forests (Hansen et al., 2013). About 3,246 km^2 of forest were lost per year in the SASSCAL region during the period 2000–2012, compared to an annual gain of merely 700 km^2 (Tab. 1). Deforestation in the region is mainly driven by clearing for agricultural purposes and expansion of settlements. Small farmers play a more important role in African deforestation than in south-east Asia and Latin America (Pröpper et al., 2010; Rudel, 2013; Parduhn & Frantz, 2018), although clearing for cash crops like tobacco also takes place. Subsistence agriculture in Miombo woodland is mainly through shifting cultivation (Fig. 8), resulting in a mosaic landscape with tree stands in different stages of succession (Chirwa et al., 2014). After clear-felling, regeneration is quick, especially through coppicing of remaining stumps, with many of the key Miombo tree species well represented (Luoga et al., 2004; Chirwa et al., 2014; Syampungani et al., 2016). However, reaching compositional similarity takes many decades (McNicol et al., 2015) and thus old growth Miombo is not common (Chidumayo, 1987b; Dewees et al., 2011). In the *Baikiaea* woodlands, farmers remain on the same fields and use short fallow periods, resulting in permanent clearings (Pröpper et al., 2010). Natural regeneration of important timber and fruit species appears problematic, especially for *Pterocarpus angolensis*, *Strychnos cocculoides*, and *G. coleosperma* in the *Baikiaea* woodlands of northern Namibia and southern Angola, and for *B. plurijuga* in Zambia (De Cauwer, 2016; DFSC, 2001; Kabajani, 2016).

Figure 8: Fresh clearance of Zambian Miombo woodland for subsistence agriculture (Photo: D. Parduhn).

While the extent of woodland degradation is difficult to assess, it is estimated that woodland degradation, including by fire, is a much larger contributor to carbon emissions than deforestation (Bombelli et al., 2009). Next to fire, the major drivers of woodland degradation in the region are slash and burn agriculture and unsustainable harvest of woodland resources (Chidumayo, 2013; Chirwa et al., 2014; Kamwi et al., 2015; Kissanga Vicente da Silva Firmino, 2016; Schelstraete, 2016). Large elephant populations can be an additional driver of woodland degradation in and near national parks of the region (Ben Shahar, 1998; Edkins et al., 2008). Wood is the main woodland resource that is unsustainably harvested (Chidumayo, 2013), although quantitative data are often too limited to assess sustainability levels (see section 5). A study in southern Angola showed that the wood biomass used by the local population of 1085 inhabitants corresponded to an area of approximately 6 hectares of Miombo woodland per year (Kissanga Vicente da Silva Firmino, 2016). In Zambia, wood harvesting for charcoal is often done in conjunction with agricultural expansion or shifting cultivation and therefore is not the primary source of woodland degradation (Parduhn & Frantz, 2018). However, when urban centres are within trading distance, woodland degradation does occur as harvesters target large canopy trees and specific tree species (e.g. Brachystegia spp.) (Zweede et al., 2006; Chidumayo, 2013; Gumbo et al., 2013; Pröpper et al., 2015). Depending on species and tree size, harvest of other woodland resources, especially bark or root fibres, can lead to tree mortality and hence forest degradation (Geldenhuys, 2004; Vermeulen, 2009; Shackleton et al., 2010; Ngubeni, 2015). Roads, and especially tar sealed roads, are the major vectors along which both deforestation and degradation takes place, especially in formerly "pristine" areas (Schneibel et al., 2013; Kamwi et al., 2015). Climate change is likely to accelerate the rate of woodland degradation in large parts of the southern African region because of increasing temperatures and changing fire regimes, especially in the areas where summer rainfall is projected to decrease (Hewitson, 2006; Enright et al., 2015; De Cauwer et al., 2016; Munalula et al., 2016). Increasing evapotranspiration caused by rising temperatures, increased fire frequency, and an increasing frequency of droughts will cause more plant stress (Munalula et al., 2016), a decrease in tree growth (Fichtler et al., 2004; Trouet et al., 2006; Therrell et al., 2007), decreasing tree recruitment (Enright et al., 2015), and ultimately a potential increase in tree mortality (Allen et al., 2010) and changing distribution ranges of tree species (Thuiller et al., 2006; De Cauwer et al., 2014). SASSCAL Task 033 showed that periods of drought and higher fire incidences in the Zambezi region of Namibia caused locals to rely even more on woodland resources, although food aid was more important still as a coping mechanism (Kamwi et al., 2015).

Both deforestation and woodland degradation affect the ability of the woodland to protect the soil, regulate the regional climate, serve as a carbon sink, and act as a safety net during droughts and wars (Chidumayo & Gumbo, 2010; Kutsch et al., 2011; Chidumayo, 2013). Woodland degradation also alters species composition, either by the survival of more fire-resistant species (De Cauwer, 2018) or by removal of species targeted for harvesting, such as *S. rautanenii* in Botswana, resulting in its listing as a threatened plant. The land-use changes and woodland degradation caused by a growing population make the region one of the world's most threatened with regard to biodiversity loss (Leadley et al., 2010). In addition, an emerging frontier of industrialised agriculture threatens large-scale conversions of dry forests and woodlands in southern Africa (Gasparri et al., 2016). Environmentally, this would be highly costly, including very negative trade-offs for biodiversity and carbon sequestration (Searchinger et al., 2015).

Woodland management

Forest and woodland monitoring

Sustainable woodland management requires knowledge of the area covered with woodlands (forest cover) and, if production of resources such as timber or carbon biomass is aimed at, information on the growing stock, total biomass and tree population dynamics. However, regional forest data are scant as no repeated national forest monitoring system is in place in any of the countries (Morales-Hidalgo, 2015). The exact forest coverage in the SASSCAL countries is also unknown. Tab. 1 lists forest cover per country based on different definitions and methodologies, each with their limitations. Data submitted to the 5- to 10-yearly forest assessment of FAO mainly consist of national desktop studies, as is the case for Angola, Botswana, Namibia, and South Africa that submitted data of low to medium quality (FAO, 2015). Desktop studies mainly concern extrapolations of outdated maps established with remote sensing, with inconsistent methods and definitions used between countries (Hansen et al., 2013; FAO, 2014b,a; De Cauwer, 2015). Zambia submitted data of good quality for forest cover as they are based on an Integrated Land Use Assessment (ILUA) project, which included repeated remote sensing surveys for the period 1990–2015 (FAO, 2014c). However, forest cover estimated with traditional optical remote sensing methods systematically underestimate the surface covered by dry tropical forest (Naidoo et al., 2016; Bastin et al., 2017). An important prerequisite for regional forest monitoring is, however, the availability of a consistent remote sensing database. The SASSCAL program explored other remote sensing methods with Tasks 032 and 033 using phenology and structural descriptors derived from long-term MODIS time series, while Task 205 used radar and LiDAR (Mathieu et al., 2018).

Estimates of the growing stock or total wood volume in the natural woodlands are often inaccurate or outdated as they are based on old forest inventories, not always covering the complete woodland area in a country (Zweede et al., 2006; De Cauwer, 2015). The most recent national forest inventory in the region appears to be in Zambia (Pohjonen, 2004), while a national forest inventory is being planned for Angola. Regional allometric equations are limited to specific species or sites (Abbot et al., 1997; Hofstad, 2005; Moses, 2013; Chidumayo, 2014), and sometimes pantropical models for aboveground biomass such as that of Chave et al. (2014) perform better than a model of another country in the region (De Cauwer, 2016). The compilation and expansion of regional datasets, especially for total biomass (including roots), is needed (Chirwa et al., 2014). Permanent sample plots allow one to derive information on woodland dynamics, especially tree growth, mortality, and regeneration (Phillips et al., 2003; Namaalwa et al., 2007), as well as the variables that influence them such as tree competition (Seifert et al., 2014). Data on tree regeneration, growth and mortality can also act as early warning for climate change (Allen et al., 2010). However, with the exception of the continuous monitoring of commercial plantations, few permanent sample plots are present in the region or their monitoring results have not been published for decades. Chidumayo (2013) recently assessed woodland degradation and recovery based on the data of permanent sample plots established in 1990 in Miombo woodland of central Zambia. The SASSCAL program established permanent sample plots in northern Namibia, while trees in the biodiversity observatories in Angola are measured and marked to allow continuous monitoring.

Another method to monitor tree growth over long periods of time is tree ring analysis. This is possible if trees have annual tree rings, as is the case in climates where there is a seasonal growth interruption because of cold temperatures or a lack of rainfall. Tree ring analysis was used by SASSCAL Task 038. It was illustrated that the mean stem diameter growth of *Pterocarpus angolensis* is 5.5 mm per year in northern Namibia and southern Angola. This is relatively high compared to growth in other parts of southern Africa (De Cauwer, 2016; Van Holsbeeck et al., 2016; De Cauwer et al., 2017). The biomass increment of *P. angolensis* in natural woodlands of northern Namibia and southern Angola is approximately 254 $kg.ha^{-1}.year^{-1}$ (De Cauwer, 2016). The sites with the highest productivity of *P. angolensis* in northern Namibia and southern Angola had a relatively lower temperature seasonality, consisted of very open woodland (canopy cover < 20% with stand BA between 5 and 10 $m^2.ha^{-1}$) and were situated on plains (De Cauwer et al., 2017). *Terminalia sericea* and *S. rautanenii* showed higher growth rates than *P. angolensis* in Namibia, while *B. africana* and *B. plurijug*a grew slower (Van Holsbeeck et al., 2016).

Regional woodland management systems

Systematic management of natural woodlands in the region is very limited (e.g. Dewees et al., 2011). Commercial timber harvesting in the region is mainly done by concessionaires. A selective harvesting system is employed, with felling of valuable timber species that have reached a minimum harvest size. Inspection for adherence to the conditions of the harvest permit is often missing because of a lack of resources in national forest agencies. Harvesting for charcoal production is mainly through clear felling, after which natural regeneration, mainly through coppicing, takes place (Shackleton & Clarke, 2007; Chidumayo, 2013).

Fire is one of the main problems that woodland managers in the region deal with. Every year, about 14% of the land area in the SASSCAL focus countries is burned (FAO, 2015). Most of this area is situated in the countries with the largest forest cover, Angola and Zambia, with 27% to 24% respectively of the land area burned on an annual basis in the period 2003–2012. The area burned annually in Namibia, Botswana, and South Africa was lower, varying between 7% and 4% respectively (FAO, 2015). A study in the Kavango-Zambezi Transfrontier Conservation Area also demonstrated that the area burned annually is high in the Angolan and Zambian, but also Namibian, parts of the conservation area, compared to Botswana and Zimbabwe where more effective fire management takes place (Pricope & Binford, 2012). Fire management of communal or state-owned woodlands is a responsibility of national forest agencies, although this is often shared with regional governments and communal forest managers. In South Africa, the government-funded job-creation program "Working on Fire" was established for implementing integrated fire management. Fire management includes both fire prevention (e.g. by establishing and maintaining firebreaks or applying early burning) and firefighting. The task is increasingly resource intensive, as the number of active fires shows a rising trend and poses an ever greater threat to the expanding population (Pricope & Binford, 2012; Schelstraete, 2016).

In Namibia, many woodland areas are managed by local communities under the Community-Based Natural Resource Management Program (CBNRM). The program aims to support and empower communities by transferring rights to manage and sell woodland resources to them. In Botswana, SASSCAL Task 311 found that the local communities support the transfer of Chobe Forest Reserve from state forest management to participatory or collaborative forest management. The communities argue that forest management regimes should be inclusive of all stakeholders, with clearly outlined roles and expectations from all parties, as it can promote a sense of ownership and hence improve protection of the reserve. However, such a collaborative approach may need an improved relationship between the stakeholders, particularly between woodland users and government officials.

Silviculture

Silviculture is the practice of tending a forest or woodland for specific purposes, for example timber, charcoal, bark and/or pole production, and includes interventions such as thinning, planting, pruning, and the use of rotations. It is rarely practised by forest managers in the SASSCAL region, except for in the commercial plantations. Hence, woodland management is restricted to the bare extraction of resources and thus can be rather compared to a mining operation where no actions are taken to invest in future woodland (Dewees et al., 2011). Cultivating indigenous fruit and timber tree species would improve food security and economic independence of local communities and it would reduce the pressure on natural forest and woodland resource stocks. SASSCAL Tasks 335 and 038 are involved in the cultivation of several indigenous tree species (De Cauwer et al., 2018).

Conclusion

Next to their important ecosystem regulating functions, the natural woodland ecosystems in the region provide an important contribution to the local and national economies. However, they are threatened by deforestation and woodland degradation, especially along roads and near population centres. Currently, woodland degradation caused by regular fires and the high dependence on wood for energy appears a bigger threat than deforestation, which is mainly caused by agricultural expansion of subsistence farmers. However, some studies predict that in the near future industrialised agricultural schemes may lead to large-scale conversion of formerly natural woodlands. Woodland managers need more data to assess the extent of forest loss and degradation, the value of the woodland resources, and the impact of climate change. Recurrent national forest inventories and access to more permanent sample plot data are therefore needed. Plantation forestry and silviculture are currently very limited and their expansion could assist in countering the trend of woodland loss.

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References

Abbot, P., Lowore, J. & Werren, M. (1997) Models for the estimation of single tree volume in four Miombo woodland types. *Forest Ecology and Management*, **97**, 25–37.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D. & Hogg, E.T. (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, **259**, 660–684.

Baptista, N. (2014) *Literature study of the woody Miombo vegetation and forest management in southeastern Angola with focus on data from the colonial era*, Polytechnic of Namibia - The Future Okavango Project, Lisbon, Portugal & Windhoek, Namibia.

Bastin, J.-F., Berrahmouni, N., Grainger, A., Maniatis, D., Mollicone, D., Moore, R., Patriarca, C., Picard, N., Sparrow, B. & Abraham, E.M. (2017) The extent of forest in dryland biomes. *Science*, **356**, 635–638.

Ben Shahar, R. (1998) Changes in structure of savanna woodlands in northern Botswana fol-

Forest resources

lowing the impacts of elephants and fire. *Plant ecology*, **136**, 189–194.
Bombelli, A., Henry, M., Castaldi, S., Adu-Bredu, S., Arneth, A., De Grandcourt, A., Grieco, E., Kutsch, W.L., Lehsten, V. & Rasile, G. (2009) The Sub-Saharan Africa carbon balance, an overview.
Burke, A. (2002) Present vegetation of the Kavango. *Journal of the Namibia Scientific Society*, **50**, 133–145.
Burke, A. (2006) Savanna trees in Namibia—Factors controlling their distribution at the arid end of the spectrum. *Flora - Morphology, Distribution, Functional Ecology of Plants*, **201**, 189–201.
Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B., Duque, A., Eid, T., Fearnside, P.M. & Goodman, R.C. (2014) Improved allometric models to estimate the aboveground biomass of tropical trees. *Global change biology*, **20**, 3177–3190.
Chidumayo, E. (1987a) A survey of wood stocks for charcoal production in the miombo woodlands of Zambia. *Forest Ecology and Management*, **20**, 105–115.
Chidumayo, E. (1987b) Woodland structure, destruction and conservation in the Copperbelt area of Zambia. *Biological Conservation*, **40**, 89–100.
Chidumayo, E.N. (2014) Estimating tree biomass and changes in root biomass following clear-cutting of Brachystegia-Julbernardia (miombo) woodland in central Zambia. *Environmental Conservation*, **41**, 54–63.
Chidumayo, E.N. (2013) Forest degradation and recovery in a miombo woodland landscape in Zambia: 22 years of observations on permanent sample plots. *Forest Ecology and Management*, **291**, 154–161.
Chidumayo, E.N. & Gumbo, D.J. (2010) *The dry forests and woodlands of Africa: managing for products and services*, Earthscan.
Childes, S.L. & Walker, B.H. (1987) Ecology and dynamics of the woody vegetation on the Kalahari sands in Hwange National Park, Zimbabwe. *Vegetatio*, **72**, 111–128.
Chirwa, P.W., Syampungani, S. & Geldenhuys, C.J. (2014) *Managing southern African woodlands for biomass production: the potential challenges and opportunities*. *Bioenergy from Wood*, pp. 67–87. Springer.
De Cauwer, V., Muys, B., Revermann, R. & Trabucco, A. (2014) Potential, realised, future distribution and environmental suitability for Pterocarpus angolensis DC in southern Africa. Forest Ecology and Management, 315, 211–226.
De Cauwer (2015) *Towards estimation of growing stock for the timber tree Pterocarpus angolensis in Namibia*. *Bridging the gap between forest information needs and forest inventory capacity*, University of Goettingen, Pietermaritzburg, South Africa.
De Cauwer, V. (2016) Autecological aspects of the African timber tree Pterocarpus angolensis in support of its sustainable management.
De Cauwer, V., Fichtler, E., Beeckman, H., Graz, F.P., Mertens, J., Van Holsbeeck, S. & Muys, B. (2017) Predicting site productivity of the timber tree Pterocarpus angolensis. *Southern Forests: a Journal of Forest Science*, 1–10.
De Cauwer, V., Geldenhuys, C.J., Aerts, R., Kabajani, M. & Muys, B. (2016) Patterns of forest composition and their long term environmental drivers in the tropical dry forest transition zone of Southern Africa. *Forest Ecosystems*, **3**, 1–12.
De Cauwer, V. & Mertens, J. (2018) Impact of fire on the Baikiaea woodlands. This volume.
De Cauwer, V., Chaka, M., Chimwamurombe, P. M., George, D., Ham, Hannel, Heita, H., Makoi, T., Mashungwa, G., Chaka, M., Reinhold-Hurek, B., & Tshwenyane, S. (2018) Artificial and assisted natural regeneration of socio-economic important southern African tree species. This volume.
Dewees, P.A., Campbell, B.M., Katerere, Y., Sitoe, A., Cunningham, A.B., Angelsen, A. & Wunder, S. (2011) *Managing the Miombo Woodlands of Southern Africa: Policies, Incentives, and Options for the Rural Poor*, Program on Forests (PROFOR), Washington D.C.
du Toit, B., Malherbe, G. F., Lambrechts, H., Naidoo, S. & Eatwell, K. (2018) Market analysis to assess timber products from dryland woodlots and farm forests in South Africa. This volume.
Edkins, M., Kruger, L., Harris, K. & Midgley, J. (2008) Baobabs and elephants in Kruger National Park: nowhere to hide. *African Journal of Ecology*, **46**, 119–125.
Enright, N.J., Fontaine, J.B., Bowman, D.M., Bradstock, R.A. & Williams, R.J. (2015) Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. *Frontiers in Ecology and the Environment*, **13**, 265–272.
FAO (2012) *FRA 2015. Terms and definitions*, FAO, Rome.
FAO (2000) Global ecological zones.
FAO (2014a) *Global Forest Resources Assessment 2015. Country report. Botswana*, FAO, Rome.
FAO (2014b) *Global Forest Resources Assessment 2015. Country report. South Africa*, FAO, Rome.
FAO (2014c) *Global Forest Resources Assessment 2015. Country report. Zambia*, FAO, Rome.
FAO (2015) *Global Forest Resources Assessment 2015. Desk reference.*, FAO, Rome.
Fichtler, E., Trouet, V., Beeckman, H., Coppin, P. & Worbes, M. (2004) Climatic signals in tree rings of Burkea africana and Pterocarpus angolensis from semiarid forests in Namibia. *Trees*, **18**, 442–451.
Forestry South Africa (2017) Abstract of South African Forestry Facts for the year 2014/2015.
Forestry South Africa (2016) Timber plantations. Getting to know the trees.
Fraser, S.W., van Rooyen, T.H. & Verster, E. (1987) Soil-plant relationships in the central Kruger National Park. *Koedoe*, **30**, 19–34.
Frost, P. (1996) *The ecology of miombo woodlands*,.
Frost, P.G.H. (2000) *Vegetation Structure of the MODIS validation site, Kataba Forest Reserve, Mongu, Zambia. Report prepared for the NASA Southern African Validation of EOS (SAVE) project, IGBP Kalahari Transect programme, and SAFARI 2000*, University of Zimbabwe, Harare, Zimbabwe.
Gasparri, N.I., Kuemmerle, T., Meyfroidt, P., Waroux, Y. & Kreft, H. (2016) The emerging soybean production frontier in Southern Africa: conservation challenges and the role of south-south telecouplings. *Conservation Letters*, **9**, 21–31.
Geldenhuys, C.J. (2004) Bark harvesting for traditional medicine: from illegal resource degradation to participatory management. *Scandinavian Journal of Forest Research*, **19**, 103–115.
Geldenhuys, C.J. & Golding, J.S. (2008) Resource use activities, conservation and management of natural resources of African savannas. *Savannas: desafios e estrategias para o equilibrio entre sociedade, agrenegocio e recursos naturais. Embrapa Cerrados, Planaltina, DF*, 225–260.
Gröngröft, A., Azebaze, N., Brown, L., Cauwer, V.D., Domptail, S., Erb, C., Falk, T., Finckh, M., Göhmann, H., Gwatidzo, C., Hinz, M., Huber, K., Jürgens, N., Korn, E., Kowalski, B., Kralisch, S., Landschreiber, L., Lubinda, A., Luther-Mosebach, J., Maiato, F., Murray-Hudson, M., Pröpper, M., Reinhold, B., Revermann, R., Simfukwe, M., Stellmes, M., Stirn, S., Thito, K., Tsheboeng, G., Weber, T., Wehberg, J., Weinzierl, T. & Zimmermann, I. (2015) *Key findings and recommendations. The Future Okavango – Findings, Scenarios and Recommendations for Action. Research Project Final Synthesis Report 2010 — 2015* (ed. by M. Pröpper), A. Gröngröft), M. Finckh), S. Stirn), V. De Cauwer), F. Lages), W. Masamba), M. Murray-Hudson), L. Schmidt), B. Strohbach), and N. Jürgens), pp. 53–96. University of Hamburg, Hamburg.
Groome, J.S., Lees, H.M.N. & Wigg, L.T. (1957) A summary of information on Pterocarpus angolensis. *Forestry Abstracts*, **18**, 1–8.
Grossmann, M.E., Mizuno, N.K., Dammen, M.L., Schuster, T., Ray, A. & Cleary, M.P. (2009) Eleostearic acid inhibits breast cancer proliferation by means of an oxidation-dependent mechanism. *Cancer Prevention Research*, **2**, 879–886.
Gumbo, D.J., Moombe, K.B., Kandulu, M.M., Kabwe, G., Ojanen, M., Ndhlovu, E. & Sunderland, T.C. (2013) *Dynamics of the charcoal and indigenous timber trade in Zambia: A scoping study in Eastern, Northern and Northwestern provinces*, CIFOR.
Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J. & Loveland, T.R. (2013) High-resolution global maps of 21st-century forest cover change. *science*, **342**, 850–853.
Headings, M.E. & Rahnema, S. (2002) The nutritional value of mopane worms, Gonimbrasia Belina (Lepidoptera: Saturniidae) for human consumption. *a presentation as part of Ten-Minute Papers, Section B, Physiology, Biochemistry, Toxicology, and Molecular Biology, Agricultural Technical Institute, The Ohio State University*.
Hewitson, B.C. (2006) *The Development of Regional Climate Change Scenarios for Sub-Saharan Africa*, International START Secretariat, Washington.
Hirota, M., Holmgren, M., Van Nes, E.H. & Scheffer, M. (2011) Global resilience of tropical forest and savanna to critical transitions. *Science*, **334**, 232–235.
Hofstad, O. (2005) Review of biomass and volume functions for individual trees and shrubs in southeast Africa. *Journal of Tropical Forest Science*, **17**, 151–162.
ITTO (2017) Muninga (Pterocarpus angolensis). *International Tropical Timber Organization: lesser used species*.

Kamwi, J.M., Chirwa, P.W.C., Manda, S.O.M., Graz, P.F. & Kätsch, C. (2015) Livelihoods, land use and land cover change in the Zambezi Region, Namibia. *Population and Environment*, **37**, 207.

Kissanga Vicente da Silva Firmino, R. (2016) Valorização da flora de Cusseque e Caiúndo no centro e sul de Angola e avaliação da biomassa lenhosa utilizada para combustível e construção.

Kutsch, W.L., Merbold, L., Ziegler, W., Mukelabai, M.M., Muchinda, M., Kolle, O. & Scholes, R.J. (2011) The charcoal trap: Miombo forests and the energy needs of people. *Carbon Balance and Management*, **6**.

Leadley, P., Pereira, H.M., Alkemade, R., Fernandez-Manjarrés, J.F., Proença, V., Scharlemann, J.P.W. & Walpole, M.J. (2010) *Biodiversity Scenarios: projections of 21st century change in biodiversity, and associated ecosystem services*, Secretariat of the Convention on Biological Diversity, Montreal.

Linard, C., Gilbert, M., Snow, R.W., Noor, A.M. & Tatem, A.J. (2012) Population Distribution, Settlement Patterns and Accessibility across Africa in 2010. *PLOS ONE*, **7**, e31743.

LPWG (2017) A new subfamily classification of the Leguminosae based on a taxonomically comprehensive phylogeny. *Taxon*, **66**, 44–77.

Luoga, E.J., Witkowski, E.T.. & Balkwill, K. (2004) Regeneration by coppicing (resprouting) of miombo (African savanna) trees in relation to land use. *Forest Ecology and Management*, **189**, 23–35.

Madzibane, J. & Potgieter, M.J. (1999) Uses of Colophospermum mopane (Leguminosae: Caesalpinioideae) by the Vhavenda. *South African Journal of Botany*, **65**, 440–444.

Mannheimer, C.A. & Curtis, B.A. eds. (2009) *Le Roux and Müller's Field Guide to the Trees and Shrubs of Namibia*, Macmillan Education Namibia, Windhoek.

Mathieu, R., Wessels, K., Main, R., Naidoo, L., van der Bergh, F. & Erasmus, B. (2018) A radar- and LiDAR-based Earth Observation system for monitoring savannah woody structure in southern Africa. This volume.

McNicol, I.M., Ryan, C.M. & Williams, M. (2015) How resilient are African woodlands to disturbance from shifting cultivation? *Ecological Applications*, **25**, 2320–2336.

Mensah, S., Veldtman, R., Assogbadjo, A.E., Ham, C., Kakaï, R.G. & Seifert, T. (2017a) Ecosystem service importance and use vary with socio-environmental factors: A study from household-surveys in local communities of South Africa. *Ecosystem Services*, **23**, 1–8.

Mensah, S., Veldtman, R. & Seifert, T. (2017b) Potential supply of floral resources to managed honey bees in natural mistbelt forests. *Journal of environmental management*, **189**, 160–167.

Mitlöhner, R. (1993) Regengrüne Baikiaea-Trockenwälder in Ost-Caprivi, Namibia. *Forstarchiv*, **64**, 264–274.

Morales-Hidalgo, D. (2015) Promoting national forest inventories. FAO's lessons learned.

Moses, M. (2013) Assessment of trade-offs between timber and carbon values of Pterocarpus angolensis (Kiaat) in the Kavango Region of Namibia - a comparison of current and potential values.

Munalula, F., Seifert, T. & Meincken, M. (2016) The Expected Effects of Climate Change on Tree Growth and Wood Quality in Southern Africa. *Springer Science Reviews*, **4**, 99–111.

Naidoo, L., Mathieu, R., Main, R., Wessels, K. & Asner, G.P. (2016) L-band Synthetic Aperture Radar imagery performs better than optical datasets at retrieving woody fractional cover in deciduous, dry savannahs. *International Journal of Applied Earth Observation and Geoinformation*, **52**, 54–64.

Namaalwa, J., Sankhayan, P.L. & Hofstad, O. (2007) A dynamic bio-economic model for analyzing deforestation and degradation: An application to woodlands in Uganda. *Forest Policy and Economics*, **9**, 479–495.

Ngubeni, N. (2015) Bark re-growth and wood decay in response to bark stripping for medicinal use.

Oliveras, I. & Malhi, Y. (2016) Many shades of green: the dynamic tropical forest–savannah transition zones. *Phil. Trans. R. Soc. B*, **371**, 20150308.

Parduhn, D. & David, F. (2018) Seeing deforestation in Zambia – On the discrepancy between biophysical land-use changes and social perception. This volume.

Phillips, P.D., Brash, T.E., Yasman, I., Subagyo, P. & Van Gardingen, P.R. (2003) An individual-based spatially explicit tree growth model for forests in East Kalimantan (Indonesian Borneo). *Ecological Modelling*, **159**, 1–26.

Phiri, D., Zulu, D., Lwali, C. & Imakando, C. (2015) Focusing on the Future of Pterocarpus chrysothrix (Mukula) in Zambia: A Brief Review of Its Ecology, Distribution and Current Threats. *International Journal of Agriculture, Forestry and Fisheries*, **3**, 218.

Piearce, G.D. (1979) A new vascular wilt disease and its relationship to widespread decline of Pterocarpus angolensis in Zambia. *Pans*, **25**, 37–45.

Pohjonen, V.M. (2004) Zambia Forest Resource Assessment 2004. *EU Forestry Support Programme in Zambia–8 ACP/051*.

Pricope, N.G. & Binford, M.W. (2012) A spatio-temporal analysis of fire recurrence and extent for semi-arid savanna ecosystems in southern Africa using moderate-resolution satellite imagery. *Journal of Environmental Management*, **100**, 72–85.

Pröpper, M., Gröngröft, A., Falk, T., Eschenbach, A., Fox, T., Gessner, U., Hecht, J., Hinz, M.O. & Huettich, C. (2010) *Causes and perspectives of land-cover change through expanding cultivation in Kavango*, Gottingen & Windhoek.

Pröpper, M., Gröngröft, A., Finckh, M., Stirn, S., De Cauwer, V., Lages, F., Masamba, W., Murray-Hudson, M., Schmidt, L., Strohbach, B. & Juergens, N. eds. (2015) *The Future Okavango - Findings, Scenarios, and Recommendations for Action. Research Project Final Synthesis Report 2010 - 2015*, University of Hamburg - Biocentre Klein Flottbek, Hamburg & Windhoek.

Putz, F.E. & Redford, K.H. (2010) The Importance of Defining 'Forest': Tropical Forest Degradation, Deforestation, Long-term Phase Shifts, and Further Transitions. *Biotropica*, **42**, 10–20.

Ratnam, J., Bond, W.J., Fensham, R.J., Hoffmann, W.A., Archibald, S., Lehmann, C.E., Anderson, M.T., Higgins, S.I. & Sankaran, M. (2011) When is a 'forest'a savanna, and why does it matter? *Global Ecology and Biogeography*, **20**, 653–660.

Revermann, R., Finckh, M., Stellmes, M., De Cauwer, V., Schroeder, B. & Oldeland (2015) Using remotely sensed predictors for SDMs to explain distribution of canopy tree species of Miombo woodlands. In Conference program and abstracts. International Biogeography Society 7th Biennial Meeting. 8–12 January 2015, Bayreuth, Germany. (ed. by D. Gavin, C. Beierkuhnlein, S. Holzheu, B. Thies, K. Faller, R.Gillespie & J. Hortal), *Frontiers of Biogeography*, **6**, suppl. 1, p. 67.

Revermann, R., Oldeland, J., Gonçalvess, F.M., Luther-Mosebach, J., Gomes, A.L., Juergens, N. & Finckh, M. (2018) Dry tropical forests and woodlands of the Cubango Basin in southern Africa: A first classification and assessment of their woody species diversity. *Phytocoenologia*, **48**, 23-50.

Rudel, T.K. (2013) The national determinants of deforestation in sub-Saharan Africa. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **368**, 20120405.

Schelstraete, M. (2016) Assessment of fire damage on the forest population near Hamoye, Kavango, Namibia.

Schneibel, A., Stellmes, M., Revermann, R., Finckh, M., Röder, A. & Hill, J. (2013) Agricultural expansion during the post-civil war period in southern Angola based on bi-temporal Landsat data. *Biodiversity and Ecology*, **5**, 311.

Scholes, R.J., Dowty, P.R., Caylor, K., Parsons, D.A.B., Frost, P.G.H. & Shugart, H.H. (2002) Trends in savanna structure and composition along an aridity gradient in the Kalahari. *Journal of Vegetation Science*, **13**, 419–428.

Searchinger, T.D., Estes, L., Thornton, P.K., Beringer, T., Notenbaert, A., Rubenstein, D., Heimlich, R., Licker, R. & Herrero, M. (2015) High carbon and biodiversity costs from converting Africa/'s wet savannahs to cropland. *Nature Climate Change*, **5**, 481–486.

Seifert, T., Seifert, S., Seydack, A., Durrheim, G. & Von Gadow, K. (2014) Competition effects in an afrotemperate forest. *Forest Ecosystems*, **1**, 1.

Shackleton, C.M. & Clarke, J.M. (2007) *Research and Management of Miombo Woodlands for Products in Support of Local Livelihoods*, Genesis Analytics. For World Bank., Johannesburg.

Shackleton, C.M. & Scholes, R.J. (2011) Above ground woody community attributes, biomass and carbon stocks along a rainfall gradient in the savannas of the central lowveld, South Africa. *South African Journal of Botany*, **77**, 184–192.

Shackleton, S., Cocks, M., Dold, T., Kaschula, S., Mbata, K., Mickels-Kokwe, G. & von Maltitz, G. (2010) Non-wood forest products: description, use and management. *EN Chidumayo and DJ Gumbo, ed*, 93–130.

Shackleton, S. & Gumbo, D. (2010) Contribution of non-wood forest products to livelihoods and poverty alleviation. *EN Chidumayo and DJ Gumbo, ed*, 63–92.

Stellmes, M., Frantz, D., Finckh, M. & Revermann, R. (2013) Okavango Basin - Earth Observation. *Biodiversity and Ecology*, **5**, 23.

Stevens, N., Swemmer, A.M., Ezzy, L. & Erasmus, B.F. (2014) Investigating potential determinants of the distribution limits of a savanna woody plant: Colophospermum mopane. *Journal of vegetation science*, **25**, 363–373.

Forest resources

Strohbach, B.J. & Petersen, A. (2007) Vegetation of the central Kavango woodlands in Namibia: An example from the Mile 46 Livestock Development Centre. *South African Journal of Botany*, **73**, 391–401.

Syampungani, S., Geldenhuys, C.J. & Chirwa, P.W. (2016) Regeneration dynamics of miombo woodland in response to different anthropogenic disturbances: forest characterisation for sustainable management. *Agroforestry systems*, **90**, 563–576.

Therrell, M.D., Stahle, D.W., Mukelabai, M.M. & Shugart, H.H. (2007) Age, and radial growth dynamics of Pterocarpus angolensis in southern Africa. *Forest Ecology and Management*, **244**, 24–31.

Thuiller, W., Midgley, G.F., Hughes, G.O., Bomhard, B., Drew, G., Rutherford, M.C. & Woodward, F. (2006) Endemic species and ecosystem sensitivity to climate change in Namibia. *Global Change Biology*, **12**, 759–776.

Timberlake, J.R. & Chidumayo, E.N. (2011) *Miombo Ecoregion vision report (revised). WWF - SARPO.*, Biodiversity Foundation for Africa, Bulawayo, Zimbabwe.

Trouet, V., Coppin, P. & Beeckman, H. (2006) Annual Growth Ring Patterns in Brachystegia spiciformis Reveal Influence of Precipitation on Tree Growth. *Biotropica*, **38**, 375–382.

Tsuzuki, T., Tokuyama, Y., Igarashi, M. & Miyazawa, T. (2004) Tumor growth suppression by α-eleostearic acid, a linolenic acid isomer with a conjugated triene system, via lipid peroxidation. *Carcinogenesis*, **25**, 1417–1425.

Van Holsbeeck, S., De Cauwer, V., De Ridder, M., Fichtler, E., Beeckman, H. & Mertens, J. (2016) Annual diameter growth of Pterocarpus angolensis (Kiaat) and other woodland species in Namibia. *Forest Ecology and Management*, **373**, 1–8.

Veldman, S., Gravendeel, B., Otieno, J.N., Lammers, Y., Duijm, E., Nieman, A., Bytebier, B., Ngugi, G., Martos, F. & van Andel, T.R. (2017) High-throughput sequencing of African chikanda cake highlights conservation challenges in orchids. *Biodiversity and Conservation*, 1–18.

Vermeulen, W.J. (2009) The sustainable harvesting of non-timber forest products from natural forests in the southern Cape, South Africa: Development of harvest systems and management prescriptions.

White, F. (1983) *The vegetation of Africa, a descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa*, Unesco, Paris.

Yeboah, E.M.O., Kobue-Lekalake, R.I., Jackson, J.C., Muriithi, E.N., Matenanga, O. & Yeboah, S.O. (2017) Application of high resolution NMR, FTIR, and GC–MS to a comparative study of some indigenous seed oils from Botswana. *Innovative Food Science & Emerging Technologies*.

Zweede, M., Safford, H. & Juergens, G. (2006) *Forest Resource Assessment Trip. Kuando Kubango Province, Angola*, USDA Forest Service.

References [CrossRef]

Abbot, P., Lowore, J. & Werren, M. (1997) Models for the estimation of single tree volume in four Miombo woodland types. *Forest Ecology and Management*, **97**, 25–37. CrossRef

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D. & Hogg, E.T. (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, **259**, 660–684. CrossRef

Baptista, N. (2014) *Literature study of the woody Miombo vegetation and forest management in southeastern Angola with focus on data from the colonial era*, Polytechnic of Namibia - The Future Okavango Project, Lisbon, Portugal & Windhoek, Namibia.

Bastin, J.-F., Berrahmouni, N., Grainger, A., Maniatis, D., Mollicone, D., Moore, R., Patriarca, C., Picard, N., Sparrow, B. & Abraham, E.M. (2017) The extent of forest in dryland biomes. *Science*, **356**, 635–638. CrossRef

Ben Shahar, R. (1998) Changes in structure of savanna woodlands in northern Botswana following the impacts of elephants and fire. *Plant ecology*, **136**, 189–194. CrossRef

Bombelli, A., Henry, M., Castaldi, S., Adu-Bredu, S., Arneth, A., De Grandcourt, A., Grieco, E., Kutsch, W.L., Lehsten, V. & Rasile, G. (2009) The Sub-Saharan Africa carbon balance, an overview.

Burke, A. (2002) Present vegetation of the Kavango. *Journal of the Namibia Scientific Society*, **50**, 133–145.

Burke, A. (2006) Savanna trees in Namibia—Factors controlling their distribution at the arid end of the spectrum. *Flora - Morphology, Distribution, Functional Ecology of Plants*, **201**, 189–201. CrossRef

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B., Duque, A., Eid, T., Fearnside, P.M. & Goodman, R.C. (2014) Improved allometric models to estimate the aboveground biomass of tropical trees. *Global change biology*, **20**, 3177–3190. CrossRef

Chidumayo, E. (1987a) A survey of wood stocks for charcoal production in the miombo woodlands of Zambia. *Forest Ecology and Management*, **20**, 105–115. CrossRef

Chidumayo, E. (1987b) Woodland structure, destruction and conservation in the Copperbelt area of Zambia. *Biological Conservation*, **40**, 89–100. CrossRef

Chidumayo, E.N. (2014) Estimating tree biomass and changes in root biomass following clear-cutting of Brachystegia-Julbernardia (miombo) woodland in central Zambia. *Environmental Conservation*, **41**, 54–63. CrossRef

Chidumayo, E.N. (2013) Forest degradation and recovery in a miombo woodland landscape in Zambia: 22 years of observations on permanent sample plots. *Forest Ecology and Management*, **291**, 154–161. CrossRef

Chidumayo, E.N. & Gumbo, D.J. (2010) *The dry forests and woodlands of Africa: managing for products and services*, Earthscan.

Childes, S.L. & Walker, B.H. (1987) Ecology and dynamics of the woody vegetation on the Kalahari sands in Hwange National Park, Zimbabwe. *Vegetatio*, **72**, 111–128.

Chirwa, P.W., Syampungani, S. & Geldenhuys, C.J. (2014) *Managing southern African woodlands for biomass production: the potential challenges and opportunities*. *Bioenergy from Wood*, pp. 67–87. Springer.

De Cauwer, V., Muys, B., Revermann, R. & Trabucco, A. (2014) Potential, realised, future distribution and environmental suitability for Pterocarpus angolensis DC in southern Africa. Forest Ecology and Management, 315, 211–226. CrossRef

De Cauwer (2015) *Towards estimation of growing stock for the timber tree Pterocarpus angolensis in Namibia*. *Bridging the gap between forest information needs and forest inventory capacity*, University of Goettingen, Pietermaritzburg, South Africa.

De Cauwer, V. (2016) Autecological aspects of the African timber tree Pterocarpus angolensis in support of its sustainable management.

De Cauwer, V., Fichtler, E., Beeckman, H., Graz, F.P., Mertens, J., Van Holsbeeck, S. & Muys, B. (2017) Predicting site productivity of the timber tree Pterocarpus angolensis. *Southern Forests: a Journal of Forest Science*, 1–10. CrossRef

De Cauwer, V., Geldenhuys, C.J., Aerts, R., Kabajani, M. & Muys, B. (2016) Patterns of forest composition and their long term environmental drivers in the tropical dry forest transition zone of Southern Africa. *Forest Ecosystems*, **3**, 1–12.

De Cauwer, V. & Mertens, J. (2018) Impact of fire on the Baikiaea woodlands. This volume. CrossRef

De Cauwer, V., Chaka, M., Chimwamurombe, P. M., George, D., Ham, Hannel, Heita, H., Makoi, T., Mashungwa, G., Chaka, M., Reinhold-Hurek, B., & Tshwenyane, S. (2018) Artificial and assisted natural regeneration of socio-economic important southern African tree species. This volume. CrossRef

Dewees, P.A., Campbell, B.M., Katerere, Y., Sitoe, A., Cunningham, A.B., Angelsen, A. & Wunder, S. (2011) *Managing the Miombo Woodlands of Southern Africa: Policies, Incentives, and Options for the Rural Poor*, Program on Forests (PROFOR), Washington D.C.

du Toit, B., Malherbe, G. F., Lambrechts, H., Naidoo, S. & Eatwell, K. (2018) Market analysis to assess timber products from dryland woodlots and farm forests in South Africa. This volume. CrossRef

Edkins, M., Kruger, L., Harris, K. & Midgley, J. (2008) Baobabs and elephants in Kruger National Park: nowhere to hide. *African Journal of Ecology*, **46**, 119–125. CrossRef

Enright, N.J., Fontaine, J.B., Bowman, D.M., Bradstock, R.A. & Williams, R.J. (2015) Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. *Frontiers in Ecology and the Environment*, **13**, 265–272. CrossRef

FAO (2012) *FRA 2015. Terms and definitions*, FAO, Rome.

FAO (2000) Global ecological zones.

FAO (2014a) *Global Forest Resources Assessment 2015. Country report. Botswana*, FAO, Rome.

FAO (2014b) *Global Forest Resources Assessment 2015. Country report. South Africa*, FAO, Rome.

FAO (2014c) *Global Forest Resources Assessment 2015. Country report. Zambia*, FAO, Rome.

FAO (2015) *Global Forest Resources Assessment 2015. Desk reference.*, FAO, Rome.

Fichtler, E., Trouet, V., Beeckman, H., Coppin, P. & Worbes, M. (2004) Climatic signals in tree rings of Burkea africana and Pterocarpus angolensis from semiarid forests in Namibia. *Trees*, **18**, 442–451. CrossRef

Forestry South Africa (2017) Abstract of South African Forestry Facts for the year 2014/2015.

Forestry South Africa (2016) Timber plantations. Getting to know the trees.

Fraser, S.W., van Rooyen, T.H. & Verster, E. (1987) Soil-plant relationships in the central Kruger National Park. *Koedoe*, **30**, 19–34. CrossRef

Frost, P. (1996) *The ecology of miombo woodlands*,.

Frost, P.G.H. (2000) *Vegetation Structure of the MODIS validation site, Kataba Forest Reserve, Mongu, Zambia. Report prepared for the NASA Southern African Validation of EOS (SAVE) project, IGBP Kalahari Transect programme, and SAFARI 2000*, University of Zimbabwe, Harare, Zimbabwe.

Gasparri, N.I., Kuemmerle, T., Meyfroidt, P., Waroux, Y. & Kreft, H. (2016) The emerging soybean production frontier in Southern Africa: conservation challenges and the role of south-south telecouplings. *Conservation Letters*, **9**, 21–31. CrossRef

Geldenhuys, C.J. (2004) Bark harvesting for traditional medicine: from illegal resource degradation to participatory management. *Scandinavian Journal of Forest Research*, **19**, 103–115.

Geldenhuys, C.J. & Golding, J.S. (2008) Resource use activities, conservation and management of natural resources of African savannas. *Savannas: desafios e estrategias para o equilibrio entre sociedade, agrenegocio e recursos naturais. Embrapa Cerrados, Planaltina, DF*, 225–260.

Gröngröft, A., Azebaze, N., Brown, L., Cauwer, V.D., Domptail, S., Erb, C., Falk, T., Finckh, M., Göhmann, H., Gwatidzo, C., Hinz, M., Huber, K., Jürgens, N., Korn, E., Kowalski, B., Kralisch, S., Landschreiber, L., Lubinda, A., Luther-Mosebach, J., Maiato, F., Murray-Hudson, M., Pröpper, M., Reinhold, B., Revermann, R., Simfukwe, M., Stellmes, M., Stirn, S., Thito, K., Tsheboeng, G., Weber, T., Wehberg, J., Weinzierl, T. & Zimmermann, I. (2015) *Key findings and recommendations*. *The Future Okavango – Findings, Scenarios and Recommendations for Action. Research Project Final Synthesis Report 2010 — 2015* (ed. by M. Pröpper), A. Gröngröft), M. Finckh), S. Stirn), V. De Cauwer), F. Lages), W. Masamba), M. Murray-Hudson), L. Schmidt), B. Strohbach), and N. Jürgens), pp. 53–96. University of Hamburg, Hamburg.

Groome, J.S., Lees, H.M.N. & Wigg, L.T. (1957) A summary of information on Pterocarpus angolensis. *Forestry Abstracts*, **18**, 1–8.

Grossmann, M.E., Mizuno, N.K., Dammen, M.L., Schuster, T., Ray, A. & Cleary, M.P. (2009) Eleostearic acid inhibits breast cancer proliferation by means of an oxidation-dependent mechanism. *Cancer Prevention Research*, **2**, 879–886. CrossRef

Gumbo, D.J., Moombe, K.B., Kandulu, M.M., Kabwe, G., Ojanen, M., Ndhlovu, E. & Sunderland, T.C. (2013) *Dynamics of the charcoal and indigenous timber trade in Zambia: A scoping study in Eastern, Northern and Northwestern provinces*, CIFOR.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J. & Loveland, T.R. (2013) High-resolution global maps of 21st-century forest cover change. *science*, **342**, 850–853. CrossRef

Headings, M.E. & Rahnema, S. (2002) The nutritional value of mopane worms, Gonimbrasia Belina (Lepidoptera: Saturniidae) for human consumption. *a presentation as part of Ten-Minute Papers, Section B, Physiology, Biochemistry, Toxicology, and Molecular Biology, Agricultural Technical Institute, The Ohio State University*.

Hewitson, B.C. (2006) *The Development of Regional Climate Change Scenarios for Sub-Saharan Africa*, International START Secretariat, Washington.

Hirota, M., Holmgren, M., Van Nes, E.H. & Scheffer, M. (2011) Global resilience of tropical forest and savanna to critical transitions. *Science*, **334**, 232–235. CrossRef

Hofstad, O. (2005) Review of biomass and volume functions for individual trees and shrubs in southeast Africa. *Journal of Tropical Forest Science*, **17**, 151–162.

ITTO (2017) Muninga (Pterocarpus angolensis). *International Tropical Timber Organization: lesser used species*.

Kamwi, J.M., Chirwa, P.W.C., Manda, S.O.M., Graz, P.F. & Kätsch, C. (2015) Livelihoods, land use and land cover change in the Zambezi Region, Namibia. *Population and Environment*, **37**, 207. CrossRef

Kissanga Vicente da Silva Firmino, R. (2016) Valorização da flora de Cusseque e Caiúndo no centro e sul de Angola e avaliação da biomassa lenhosa utilizada para combustível e construção.

Kutsch, W.L., Merbold, L., Ziegler, W., Mukelabai, M.M., Muchinda, M., Kolle, O. & Scholes, R.J. (2011) The charcoal trap: Miombo forests and the energy needs of people. *Carbon Balance and Management*, **6**. CrossRef

Leadley, P., Pereira, H.M., Alkemade, R., Fernandez-Manjarrés, J.F., Proença, V., Scharlemann, J.P.W. & Walpole, M.J. (2010) *Biodiversity Scenarios: projections of 21st century change in biodiversity, and associated ecosystem services*, Secretariat of the Convention on Biological Diversity, Montreal.

Linard, C., Gilbert, M., Snow, R.W., Noor, A.M. & Tatem, A.J. (2012) Population Distribution, Settlement Patterns and Accessibility across Africa in 2010. *PLOS ONE*, **7**, e31743. CrossRef

LPWG (2017) A new subfamily classification of the Leguminosae based on a taxonomically comprehensive phylogeny. *Taxon*, **66**, 44–77. CrossRef

Luoga, E.J., Witkowski, E.T.. & Balkwill, K. (2004) Regeneration by coppicing (resprouting) of miombo (African savanna) trees in relation to land use. *Forest Ecology and Management*, **189**, 23–35. CrossRef

Madzibane, J. & Potgieter, M.J. (1999) Uses of Colophospermum mopane (Leguminosae: Caesalpinioideae) by the Vhavenda. *South African Journal of Botany*, **65**, 440–444. CrossRef

Mannheimer, C.A. & Curtis, B.A. eds. (2009) *Le Roux and Müller's Field Guide to the Trees and Shrubs of Namibia*, Macmillan Education Namibia, Windhoek.

Mathieu, R., Wessels, K., Main, R., Naidoo, L., van der Bergh, F. & Erasmus, B. (2018) A radar- and LiDAR-based Earth Observation system for monitoring savannah woody structure in southern Africa. This volume. CrossRef

McNicol, I.M., Ryan, C.M. & Williams, M. (2015) How resilient are African woodlands to disturbance from shifting cultivation? *Ecological Applications*, **25**, 2320–2336. CrossRef

Mensah, S., Veldtman, R., Assogbadjo, A.E., Ham, C., Kakaï, R.G. & Seifert, T. (2017a) Ecosystem service importance and use vary with socio-environmental factors: A study from household-surveys in local communities of South Africa. *Ecosystem Services*, **23**, 1–8. CrossRef

Mensah, S., Veldtman, R. & Seifert, T. (2017b) Potential supply of floral resources to managed honey bees in natural mistbelt forests. *Journal of environmental management*, **189**, 160–167. CrossRef

Mitlöhner, R. (1993) Regengrüne Baikiaea-Trockenwälder in Ost-Caprivi, Namibia. *Forstarchiv*, **64**, 264–274.

Morales-Hidalgo, D. (2015) Promoting national forest inventories. FAO's lessons learned.

Moses, M. (2013) Assessment of trade-offs between timber and carbon values of Pterocarpus angolensis (Kiaat) in the Kavango Region of Namibia - a comparison of current and potential values.

Munalula, F., Seifert, T. & Meincken, M. (2016) The Expected Effects of Climate Change on Tree Growth and Wood Quality in Southern Africa. *Springer Science Reviews*, **4**, 99–111. CrossRef

Naidoo, L., Mathieu, R., Main, R., Wessels, K. & Asner, G.P. (2016) L-band Synthetic Aperture Radar imagery performs better than optical datasets at retrieving woody fractional cover in deciduous, dry savannahs. *International Journal of Applied Earth Observation and Geoinformation*, **52**, 54–64. CrossRef

Namaalwa, J., Sankhayan, P.L. & Hofstad, O. (2007) A dynamic bio-economic model for analyzing deforestation and degradation: An application to woodlands in Uganda. *Forest Policy and Economics*, **9**, 479–495. CrossRef

Ngubeni, N. (2015) Bark re-growth and wood decay in response to bark stripping for medicinal use.

Oliveras, I. & Malhi, Y. (2016) Many shades of green: the dynamic tropical forest–savannah transition zones. *Phil. Trans. R. Soc. B*, **371**, 20150308. CrossRef

Parduhn, D. & David, F. (2018) Seeing deforestation in Zambia – On the discrepancy between biophysical land-use changes and social perception. This volume. CrossRef

Phillips, P.D., Brash, T.E., Yasman, I., Subagyo, P. & Van Gardingen, P.R. (2003) An individual-based spatially explicit tree growth model for forests in East Kalimantan (Indonesian Borneo). *Ecological Modelling*, **159**, 1–26. CrossRef

Phiri, D., Zulu, D., Lwali, C. & Imakando, C. (2015) Focusing on the Future of Pterocarpus chrysothrix (Mukula) in Zambia: A Brief Review of Its Ecology, Distribution and Current Threats. *International Journal of Agriculture, Forestry and Fisheries*, **3**, 218.

Pierace, G.D. (1979) A new vascular wilt disease and its relationship to widespread decline of Pterocarpus angolensis in Zambia. *Pans*, **25**, 37–45.

Pohjonen, V.M. (2004) Zambia Forest Resource Assessment 2004. *EU Forestry Support Programme in Zambia–8 ACP/051*.

Pricope, N.G. & Binford, M.W. (2012) A spatio-temporal analysis of fire recurrence and extent for semi-arid savanna ecosystems in southern Africa using moderate-resolution satellite imagery. *Journal of Environmental Management*, **100**, 72–85. CrossRef

Pröpper, M., Gröngröft, A., Falk, T., Eschenbach, A., Fox, T., Gessner, U., Hecht, J., Hinz, M.O. & Huettich, C. (2010) *Causes and perspectives of land-cover change through expanding cultivation in Kavango*, Gottingen & Windhoek.

Pröpper, M., Gröngröft, A., Finckh, M., Stirn, S., De Cauwer, V., Lages, F., Masamba, W., Murray-Hudson, M., Schmidt, L., Strohbach, B. & Juergens, N. eds. (2015) *The Future Okavango - Findings, Scenarios, and Recommendations for Action. Research Project Final Synthesis Report 2010 - 2015*, University of Hamburg - Biocentre Klein Flottbek, Hamburg & Windhoek.

Putz, F.E. & Redford, K.H. (2010) The Importance of Defining 'Forest': Tropical Forest Degradation, Deforestation, Long-term Phase Shifts, and Further Transitions. *Biotropica*, **42**, 10–20. CrossRef

Ratnam, J., Bond, W.J., Fensham, R.J., Hoffmann, W.A., Archibald, S., Lehmann, C.E., Anderson, M.T., Higgins, S.I. & Sankaran, M. (2011) When is a 'forest'a savanna, and why does it matter? *Global Ecology and Biogeography*, **20**, 653–660. CrossRef

Revermann, R., Finckh, M., Stellmes, M., De Cauwer, V., Schroeder, B. & Oldeland (2015) Using remotely sensed predictors for SDMs to explain distribution of canopy tree species of Miombo woodlands. In Conference program and abstracts. International Biogeography Society 7th Biennial Meeting. 8–12 January 2015, Bayreuth, Germany. (ed. by D. Gavin, C. Beierkuhnlein, S. Holzheu, B. Thies, K. Faller, R.Gillespie & J. Hortal), *Frontiers of Biogeography*, **6**, suppl. 1, p. 67.

Revermann, R., Oldeland, J., Gonçalvess, F.M., Luther-Mosebach, J., Gomes, A.L., Juergens, N. & Finckh, M. (2018) Dry tropical forests and woodlands of the Cubango Basin in southern Africa: A first classification and assessment of their woody species diversity. *Phytocoenologia*, **48**, 23-50. CrossRef

Rudel, T.K. (2013) The national determinants of deforestation in sub-Saharan Africa. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **368**, 20120405. CrossRef

Schelstraete, M. (2016) Assessment of fire damage on the forest population near Hamoye, Kavango, Namibia.

Schneibel, A., Stellmes, M., Revermann, R., Finckh, M., Röder, A. & Hill, J. (2013) Agricultural expansion during the post-civil war period in southern Angola based on bi-temporal Landsat data. *Biodiversity and Ecology*, **5**, 311. CrossRef

Scholes, R.J., Dowty, P.R., Caylor, K., Parsons, D.A.B., Frost, P.G.H. & Shugart, H.H. (2002) Trends in savanna structure and composition along an aridity gradient in the Kalahari. *Journal of Vegetation Science*, **13**, 419–428. CrossRef

Searchinger, T.D., Estes, L., Thornton, P.K., Beringer, T., Notenbaert, A., Rubenstein, D., Heimlich, R., Licker, R. & Herrero, M. (2015) High carbon and biodiversity costs from converting Africa/'s wet savannahs to cropland. *Nature Climate Change*, **5**, 481–486. CrossRef

Seifert, T., Seifert, S., Seydack, A., Durrheim, G. & Von Gadow, K. (2014) Competition effects in an afrotemperate forest. *Forest Ecosystems*, **1**, 1. CrossRef

Shackleton, C.M. & Clarke, J.M. (2007) *Research and Management of Miombo Woodlands for Products in Support of Local Livelihoods*, Genesis Analytics. For World Bank., Johannesburg. CrossRef

Shackleton, C.M. & Scholes, R.J. (2011) Above ground woody community attributes, biomass and carbon stocks along a rainfall gradient in the savannas of the central lowveld, South Africa. *South African Journal of Botany*, **77**, 184–192.

Shackleton, S., Cocks, M., Dold, T., Kaschula, S., Mbata, K., Mickels-Kokwe, G. & von Maltitz, G. (2010) Non-wood forest products: description, use and management. *EN Chidumayo and DJ Gumbo, ed*, 93–130.

Shackleton, S. & Gumbo, D. (2010) Contribution of non-wood forest products to livelihoods and poverty alleviation. *EN Chidumayo and DJ Gumbo, ed*, 63–92.

Stellmes, M., Frantz, D., Finckh, M. & Revermann, R. (2013) Okavango Basin - Earth Observation. *Biodiversity & Ecology*, **5**, 23. CrossRef

Stevens, N., Swemmer, A.M., Ezzy, L. & Erasmus, B.F. (2014) Investigating potential determinants of the distribution limits of a savanna woody plant: Colophospermum mopane. *Journal of vegetation science*, **25**, 363–373. CrossRef

Strohbach, B.J. & Petersen, A. (2007) Vegetation of the central Kavango woodlands in Namibia: An example from the Mile 46 Livestock Development Centre. *South African Journal of Botany*, **73**, 391–401. CrossRef

Syampungani, S., Geldenhuys, C.J. & Chirwa, P.W. (2016) Regeneration dynamics of miombo woodland in response to different anthropogenic disturbances: forest characterisation for sustainable management. *Agroforestry systems*, **90**, 563–576. CrossRef

Therrell, M.D., Stahle, D.W., Mukelabai, M.M. & Shugart, H.H. (2007) Age, and radial growth dynamics of Pterocarpus angolensis in southern Africa. *Forest Ecology and Management*, **244**, 24–31. CrossRef

Thuiller, W., Midgley, G.F., Hughes, G.O., Bomhard, B., Drew, G., Rutherford, M.C. & Woodward, F. (2006) Endemic species and ecosystem sensitivity to climate change in Namibia. *Global Change Biology*, **12**, 759–776. CrossRef

Timberlake, J.R. & Chidumayo, E.N. (2011) *Miombo Ecoregion vision report (revised). WWF - SARPO.*, Biodiversity Foundation for Africa, Bulawayo, Zimbabwe.

Trouet, V., Coppin, P. & Beeckman, H. (2006) Annual Growth Ring Patterns in Brachystegia spiciformis Reveal Influence of Precipitation on Tree Growth. *Biotropica*, **38**, 375–382. CrossRef

Tsuzuki, T., Tokuyama, Y., Igarashi, M. & Miyazawa, T. (2004) Tumor growth suppression by α-eleostearic acid, a linolenic acid isomer with a conjugated triene system, via lipid peroxidation. *Carcinogenesis*, **25**, 1417–1425. CrossRef

Van Holsbeeck, S., De Cauwer, V., De Ridder, M., Fichtler, E., Beeckman, H. & Mertens, J. (2016) Annual diameter growth of Pterocarpus angolensis (Kiaat) and other woodland species in Namibia. *Forest Ecology and Management*, **373**, 1–8. CrossRef

Veldman, S., Gravendeel, B., Otieno, J.N., Lammers, Y., Duijm, E., Nieman, A., Bytebier, B., Ngugi, G., Martos, F. & van Andel, T.R. (2017) High-throughput sequencing of African chikanda cake highlights conservation challenges in orchids. *Biodiversity and Conservation*, 1–18. CrossRef

Vermeulen, W.J. (2009) The sustainable harvesting of non-timber forest products from natural forests in the southern Cape, South Africa: Development of harvest systems and management prescriptions.

White, F. (1983) *The vegetation of Africa, a descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa*, Unesco, Paris.

Yeboah, E.M.O., Kobue-Lekalake, R.I., Jackson, J.C., Muriithi, E.N., Matenanga, O. & Yeboah, S.O. (2017) Application of high resolution NMR, FTIR, and GC–MS to a comparative study of some indigenous seed oils from Botswana. *Innovative Food Science & Emerging Technologies*. CrossRef

Zweede, M., Safford, H. & Juergens, G. (2006) *Forest Resource Assessment Trip. Kuando Kubango Province, Angola*, USDA Forest Service.

Patterns of above-ground biomass and its environmental drivers: an analysis based on plot-based surveys in the dry tropical forests and woodlands of southern Africa

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Abstract: In this paper we present an estimate of above-ground biomass (AGB) in the dry tropical forests and woodlands of southern Angola, western Zambia, northern Namibia and northern Botswana. Furthermore, we investigated the environmental variables influencing the spatial distribution of AGB. We compiled data from 498 vegetation plots and forest inventories covering seven vegetation types. The dataset contained measurements of 8803 individual trees belonging to 167 different species. The frequency of the trees per diameter at breast height (DBH) classes indicated healthy community structures with all vegetation types of miombo (Zambia and Angola), *Baikiaea* (Angola and Namibia), *Baikiaea-Combretum*, mopane, and *Terminalia* showing high number of trees in the smaller classes. We used two regional allometric equations developed for the miombo woodlands by Ryan (2011) and Chidumayo (2013) to calculate AGB. The highest AGB was recorded in the miombo woodlands of Zambia (median = 82.2 t/ha), followed by the dense *Baikiaea-Combretum* woodlands in Angola (median = 61 t/ha) and the Angolan miombo woodlands (median = 60.4 t/ha). Using generalized linear models, we analysed the relationship of AGB and environmental variables. Mean annual precipitation had the highest predictive power, explaining almost two thirds of the variance. Our conclusion was that, at regional scale, climate is a key driver of vegetation patterns, and biomass is no exception. There is a high local variability, however, that cannot completely be explained by gridded environmental datasets.

Resumo: Neste artigo, apresentamos uma estimativa da biomassa acima do solo (AGB) em florestas tropicais secas e bosques do Sul de Angola, Oeste da Zâmbia, Norte da Namíbia e Norte do Botswana. Além disso, investigamos as variáveis que influenciam a distribuição espacial da AGB. Compilámos dados de 498 parcelas de vegetação e inventários florestais, cobrindo sete tipos de vegetação. O conjunto de dados continha medições de 8803 árvores individuais, pertencentes a 167 espécies diferentes. A frequência das classes de árvores por diâmetro à altura do peito (DBH) indicou estruturas comunitárias saudáveis com todos os tipos de vegetação de miombo (Zâmbia e Angola), *Baikiaea* (Angola e Namíbia), *Baikiaea-Combretum*, mopane e *Terminalia*, mostrando um grande número de árvores nas classes mais pequenas. Utilizámos duas equações alométricas regionais, desenvolvidas para bosques de miombo por Ryan (2011) e Chidumayo (2013), para calcular a AGB. A mais elevada AGB foi registada nos bosques de miombo da Zâmbia (mediana = 82,2 t/ha), seguida pelos bosques densos de *Baikiaea-Combretum* em Angola (mediana = 61 t/ha) e os bosques de miombo angolano (mediana = 60,4 t/ha). Com recurso aos modelos lineares generalizados, analisamos a relação entre a AGB e variáveis ambientais. A precipitação média anual teve o maior poder preditivo, explicando quase dois terços da variância. A nossa conclusão foi que, à escala regional, o clima é um factor importante para os padrões da vegetação, e a biomassa não é excepção. Existe uma elevada variabilidade local, no entanto, esta não pode ser completamente explicada pelo elevado conjunto de dados ambientais.

Introduction

Dry tropical forests and woodlands cover large parts of southern Africa and are present in all five SASSCAL countries. They occur mainly in the northern, more mesic parts of the region that have a marked dry season lasting for several months per year but still receive sufficient precipitation during the wet season to support the growth of broad-leafed trees, reaching canopy heights well above ten meters (De Cauwer et al., 2018). From a floristic perspective, most of the woodlands in southern Africa fall into the Zambezian Phytoregion (White, 1983). Most of the dominant species of the tree layer belong to the Fabaceae family, but species of the Rubiaceae and Combretaceae play an important role too (Chidumayo & Gumbo, 2010). Ecosystem services from these woodlands provide important contributions to the livelihoods of over 100 million rural people and 50 million urban dwellers, mitigating some of the symptoms of the chronic poverty in the region (Dewees et al., 2010). As such, the woodlands provide the local population with several products ranging from timber and fuelwood to charcoal, honey, construction materials, and medicine. Furthermore, they are crucial for carbon storage, the water cycle, and climate regulation (Chidumayo, 1997; Frost, 1996; Ryan et al., 2011). As such, woodlands play a broad, twofold role: first, providing valuable ecosystem services such as increasing resilience through protecting watersheds and stream-flows, controlling erosion, enhancing soil fertility, regulating the climate, and protecting biodiversity; and, second, serving as a diverse source of jobs and livelihoods for African economies and citizens.

Understanding the spatial patterns of biomass in the Zambezian Phytoregion is important for providing insight into biomass variation and the influence of the environment, providing information on the carbon emissions related to land use change, establishing carbon mapping schemes, and modelling responses of the woodlands to their changing environment. African tropical forests and woodlands have been characterised by previous studies (Brown, 1997; Chave et al., 2005) as holding relatively high carbon stocks.

The decrease in dry tropical forests and woodlands in Africa is alarmingly severe as a result of overutilization and land use changes (Dewees et al., 2010). The protection and sustainable management of forest carbon stocks, particularly in the tropics, is a key factor in mitigating global change effects. Nevertheless, our knowledge of how the environment affects carbon stocks in tropical ecosystems needs to be improved. For a sustainable management of woodlands and forests, spatial and temporal information on ecosystem structure, species composition, and biomass (carbon stocks) is indispensable (Thompson et al., 2012). Ground-based information is sparse to absent for vast parts of south-central Africa, however. In contrast to tropical rainforests, dry tropical forests and woodlands have not been the focus of research (Bodart et al., 2013) and ground-based studies and forest inventories are scarce (Tewari, 2016).

Instead, several studies have tried to estimate the above-ground biomass (AGB) of forests in tropical regions using modelling and remote sensing approaches. Saatchi et al. (2011) developed a benchmark map of forest carbon stocks in the tropical regions across three continents. This study used a combination of data from in situ inventory plots and remote sensing to extrapolate from a spatially biased and limited number of ground measurements to predict biomass for the entire tropics.

Estimates of forest AGB are approximations relying on a combination of land cover type and corresponding mean carbon derived from field surveys, instead of spatially explicit biomass maps (Carreiras et al., 2013). In the field, the AGB of woodlands can be estimated based on allometric equations that relate the breast height diameter (DBH) of a tree, a common measurement used in forest inventories, to its biomass. These equations are based on destructive harvesting and subsequent weighing of the biomass of the tree and are thus very labour-intensive. However, the established relationship between DBH and AGB allows the rapid quantification of AGB for forest stands solely based on measurements of the DBH of the individual trees. A number of comprehensive allometric models for biomass estimation have been developed for the major forests and woodlands in Europe, the Americas, and Asia (Chave et al., 2014). In countries of sub-Saharan Africa, most studies estimating biomass or carbon stocks have also used allometric models together with forest inventory data (Mate et al., 2014; Mwakalukwa et al., 2014; Halperin et al., 2016). Ideally, allometric equations are developed for the specific woodland type in question, as the relationship is sensitive to species, and also the prevailing environmental conditions at the sites.

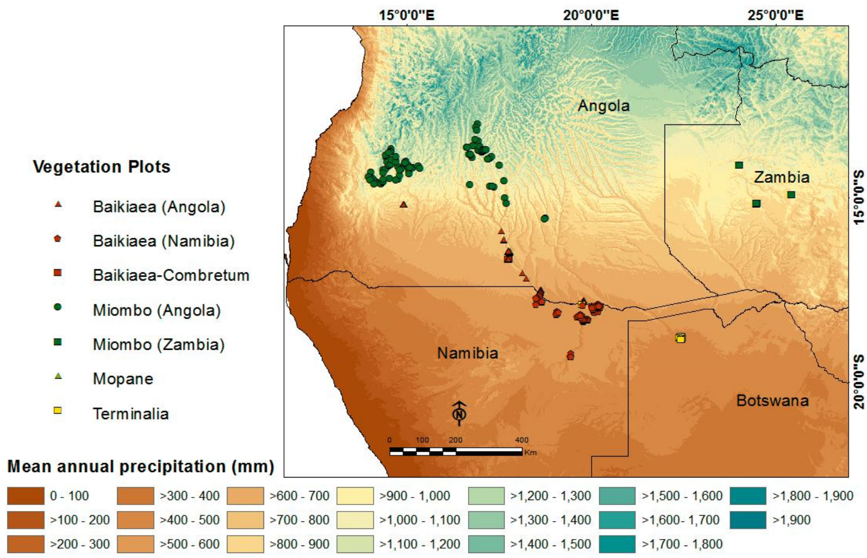

Figure 1: Map of the study sites and the seven vegetation types.

The objectives of this paper are:

1. to provide an estimate of AGB of the dry tropical forests and woodlands of southern Africa based on tree measurements in the field using two allometric equations, and
2. to investigate the environmental drivers of AGB on a regional scale.

Methods

The study was carried out in dry tropical forests and woodlands of Angola, Botswana, Namibia, and Zambia (Fig. 1, Tab. 1). The sampled area covers a strong precipitation gradient ranging from the semi-arid Kalahari Desert in northern Botswana, with mean annual precipitation of 500 mm, to the semi-humid areas in north-western Zambia and central Angola, which receive up to 1,400 mm of yearly precipitation. Differences in mean annual temperature are less pronounced, ranging from 21 to 23°C. The study area is mostly covered by Kalahari sands, making arenosols with low nutrient content the dominant soil types. The western parts of the study area in Angola's Huíla and Bíe provinces, however, have a different underlying geology, and the common soil types are ferrasols.

Central Angola and Zambia are covered by brevi-deciduous miombo woodlands, which are dominated by *Brachystegia* species and *Julbernardia paniculata* (Tab. 1). The canopy is more or less closed and reaches heights well above 10 meters, and in Zambia even above 20 m (De Cauwer et al., 2018; Revermann et al., 2018). With decreasing precipitation southwards, the miombo woodlands give way to *Baikiaea* woodlands characterised by an interrupted canopy closure (De Cauwer et al., 2016; Revermann et al., 2018). The most southerly and driest part included in this study is north of the Okavango Delta, where mopane woodlands

Table 1: Most frequent species of the vegetation types and prevailing environmental conditions at the plot locations; mean values are given and the standard deviation in brackets; the temperature range was presented as the mean of the monthly range of the minimum and maximum temperatures.

Woodland type	Most frequent species	Total annual precipitation (mm)	Temperature range (°C)	Silt content topsoil (%)	Coarse fragments topsoil (%)	Fire frequency (number of years)	Human impact index
Miombo (Angola)	*Julbernardia paniculata, Brachystegia spiciformis, Brachystegia longifolia, Brachystegia spp. 2*	1123 (129)	10.7 (0.9)	11.2 (3.4)	4 (3)	0.8 (1.6)	17 (3)
Miombo (Zambia)	*Julbernardia paniculata, Brachystegia boehmii, Diospyros batocana, Guibourtia coleosperma*	999 (38)	9.6 (0.1)	26.5 (4)	0.8 (1.2)	0 (0)	14 (2)
Baikiaea (Angola)	*Baikiaea plurijuga, Burkea africana, Combretum collinum, Erythrophleum africanum*	689 (76)	11.1 (0.4)	10.3 (3.4)	4.6 (3.8)	2.4 (2.1)	12 (2)
Baikiaea-*Combretum*	*Baikiaea plurijuga, Philenoptera nelsii, Commiphora tenuiptulata, Acacia ataxacantha*	739 (6)	10.9 (0)	16 (2)	0.6 (0.5)	0 (0)	9 (0)
Baikiaea (Namibia)	*Baikiaea plurijuga, Philenoptera nelsii, Commiphora tenuiptulata, Acacia ataxacantha*	572 (24)	11.2 (0.1)	9.6 (2.7)	4.9 (3.6)	1.7 (1.6)	12 (5)
Mopane	*Colophospermum mopane, Baikiaea plurijuga, Acacia erioloba, Philenoptera nelsii*	476 (5)	11.2 (0.1)	8.8 (1.3)	1.9 (0.9)	0.4 (0.5)	10 (2)
Terminalia	*Terminalia sericea, Combretum collinum, Acacia erioloba, Burkea africana*	478 (22)	11.2 (0)	8.9 (3)	1.8 (1.5)	0.2 (0.4)	12 (6)

and *Terminalia* shrublands dominate. Trees in dense woodland or more open savanna woodland may reach heights of 10 m to 15 m in deep alluvial soils, and attain 25 m in the 'cathedral mopane' of Zambia (Ben-Shahar, 1998). Mopane tends to be stunted and shrubby (1–3 m) where it occurs in impermeable alkaline soils (Vermeulen, 1996).

Sampling design

For this analysis, we compiled data on tree measurements from different plot-based surveys. We included data from the Vegetation Database of the Okavango Basin (Revermann, 2016) from SASSCAL biodiversity observatories (Zambia: S51 Luampa, S52 Dongwe, S53 Kafue National Park; Angola: S74 Cusseque, S75 Bicuar National Park), from the Vegetation Survey of Huíla Province (Chisingui et al., 2018), and from the forest inventory in northern Namibia (De Cauwer et al., 2016). Vegetation plots of the surveys and on the biodiversity observatories were sized 20 m × 50 m. The sample plots of forest inventory in Namibia and in southern Angola followed a circular, nested design with a maximum radius of 30 m, as suggested for Namibia forest inventories by Burke et al. (2001). In every plot, all trees above a certain diameter at breast height (DBH) threshold were measured for height and DBH. As the threshold varied in the different surveys, we considered only trees with a DBH > 10 cm. Based on these measurements, the AGB was estimated using allometric equations. As results obtained by different equations calibrated at different locations can vary substantially (Ciais et al., 2011), we used two equations from the miombo region, to obtain an idea of the uncertainty caused by the use of different allometric equations. Equation 1 was calibrated in Mozambique by Ryan et al. (2011) and provides an estimate of the carbon content of the stem. We used the generally accepted ratio of the carbon fraction in woody dry matter of 0.47 (Eggleston et al., 2006) to convert carbon to AGB. Equation 2 was calibrated in the miombo woodlands of Zambia (Chidumayo, 2013). Finally, the aggregated biomass in kilograms per plot was converted to tonnes per hectare.

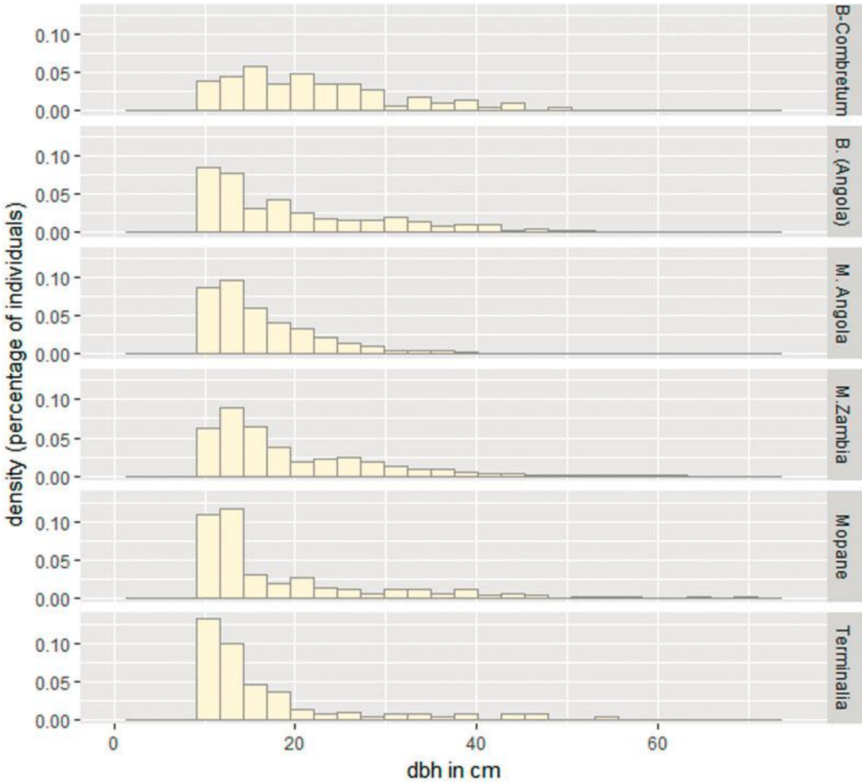

Figure 2: Size class distribution of the measured trees in each major vegetation type *Baikiaea-Combretum*, *Baikiaea* (Angola), miombo (Angola), miombo (Zambia), mopane, and *Terminalia*; only trees with DBH > 10 cm were considered (no diagram for *Baikiaea* woodlands in Namibia is displayed).

Eq. 1: $\ln(B_{stem}) = 2.601 \ln(DBH) - 3.629$

Eq. 2: $\ln(AGB) = 2.5553 \ln(DBH) - 2.5265$

where *DBH* is the stem diameter at breast height in cm, *ln* is the natural logarithm; *AGB* is the above-ground dry biomass in kg, and B_{stem} is the AGB of the stem in kg C.

Statistical analyses

To provide figures for the different sub-regions of the study area, the plots were grouped into seven major vegetation types: miombo woodlands in Angola and Zambia, *Baikiaea* woodlands in Angola and Namibia, *Baikiaea-Combretum* woodlands with thicket-like understorey (this vegetation type mainly occurs in certain parts of southern Cuando Cubango Province in Angola; for a description of this rare woodland type see Wallenfang et al., 2015), mopane woodlands, and *Terminalia* shrublands (Fig. 1). To visualize the structure and population status of the different vegetation types, we calculated size class distribution curves.

To investigate the environmental drivers of spatial patterns of AGB, we compiled environmental data from various sources covering the entire region. Bioclimatic data were derived from CHELSA Climate Database (Karger et al., 2017); information on soil nutrients, soil texture, soil pH, and conductivity in the top- and subsoils were calculated for each plot location based on the data from the global soils database (Hengl et al., 2017; soilgrids.org). As disturbance and land use history are crucial factors influencing vegetation patterns, we furthermore included information on fire frequency and fire season derived from the MODIS burned area product (Stellmes et al., 2013). These variables along with the major vegetation types (see above) were used as predictor variables in a general linearized model (GLM) with AGB as the response variable assuming a gamma distribution. Predictor variables were checked for collinearity among pairs of predictor variables using the Pearson coefficient of correlation. In the case of high collinearity, one of a pair of highly correlated variables was removed from the set of variables (Dormann et al., 2013). The minimum adequate model was identified based on backward variable selection and the Akaike information criterion.

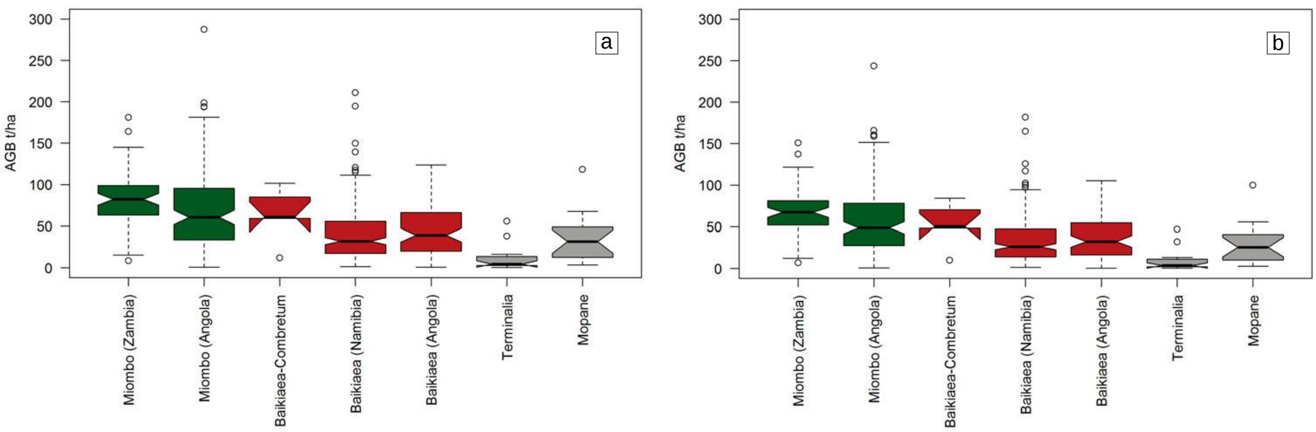

Figure 3: Estimated AGB (t/ha) according to the major vegetation types in the study area based on DBH measurements of individual trees and allometric equations by Ryan et al. (2011) (a) and Chidumayo (2013) (b).

Results

In total, 8803 individual trees were measured. A cumulative total of 167 woody species, 7 of which had not been identified to the genus level, were recorded. The species that were most abundant in the miombo woodlands were *Julbernardia paniculata*, *Brachystegia boehmii*, *B. spiciformis*, *B. longifolia,* and *Cryptosepalum exfoliatum* subsp. *pseudotaxus*. Common trees of the *Baikiaea* woodlands besides the species *Baikiaea plurijuga* were *Burkea africana, Combretum collinum, Erythrophleum africanum,* and *Philenoptera nelsii*. At the study site in Botswana, *Colophospermum mopane*, *Terminalia sericea*, *Acacia erioloba,* and *Philenoptera nelsii* were dominant (Tab. 1).

Though the *Baikiaea* woodlands had the thickest trees, tree densities were much lower; indeed, the miombo with the highest tree density in Zambia was five times denser than the *Baikiaea* woodlands with the lowest tree density in southern Angola (De Cauwer et al., 2018). The frequency of trees per DBH class for the seven major vegetation types showed a higher number of trees in the smaller classes in all vegetation types (Fig. 2).

Both allometric equations resulted in similar relative patterns of the distribution of AGB within vegetation types (Fig. 3, Tab. 2). AGB_{Ryan} provided a constant lower estimate compared to $AGB_{Chidumayo}$. The highest AGB was found in the miombo woodlands of Zambia, followed by the *Baikiaea-Combretum* woodlands in south Angola and the Angolan miombo woodlands. The AGB in the Angolan *Baikiaea* woodlands was slightly higher than that of the *Baikiaea* woodlands in Namibia and the mopane woodlands in Botswana. *Terminalia* shrublands had the lowest values in the entire study (Fig. 3, Tab. 2). It needs to be highlighted that there was high variation within the dataset, indicated by the high median absolute deviation (MAD) for all vegetation types.

Table 2: Summary of above-ground biomass (AGB) in tonnes per ha according to the four major vegetation types and for the two allometric equations (Eq. 1 × 0.47, Ryan et al. [2011]; Eq. 2, Chidumayo [2013]). The median per vegetation type is given, and the variation is depicted by the median absolute deviation (MAD).

	AGB_{Ryan} (t/ha)		$AGB_{Chidumayo}$(t/ha)	
Major vegetation type	**Median**	**MAD**	**Median**	**MAD**
Miombo woodlands (Zambia)	67.2	20.7	82.2	24.6
Miombo woodlands (Angola)	48.8	37.2	60.4	45.5
Baikiaea-Combretum woodlands	50.2	29.8	61.0	35.6
Baikiaea woodlands (Angola)	32.5	27.8	39.2	33.5
Baikiaea woodlands (Namibia)	26.3	20.1	32.1	24.2
Mopane woodlands	25.6	22.9	31.5	28.2
Terminalia shrublands	3.7	3.4	4.6	4.2
total	35.3	32.6	42.9	39.5

Environmental drivers of above-ground biomass

Many of the climate variables showed strong collinearity, so one variable from each highly correlated pair had to be removed as a predictor variable. The same held true for the soil variables. The final models, with $AGB_{Chidumayo}$ and AGB_{Ryan} as response variables, contained the same predictor variables and displayed very similar model coefficients (Tab. 3). They both showed fairly low performance, with 16.1% and 15.3% explained deviance respectively. In the following, we will present results only for the model based on $AGB_{Chidumayo}$.

The variable with the highest predictive power was mean annual precipitation, explaining almost two thirds of the variance (Tab. 3). Generally, regions with higher precipitation showed higher AGB (Fig. 4). Mean annual precipitation exhibited a strong negative correlation with mean annual temperature. The second most important variable was silt content of the topsoil, explaining one fifth of the variance. Each of the remaining predictor variables contributed less than 10% to the explained variance (Tab. 3, Fig. 4).

Discussion

Stand structure and above-ground biomass

Tree size distributions are a simple yet effective tool for describing tree populations and woodland stands, and the distribution of diameters is the most potent simple factor for depicting the properties of a stand of trees (Ferreira de Lima et al., 2014). The community structure — the shape of the diameter distribution for all the vegetation types in our study — was typical for self-regenerating communities: the highest numbers of individuals were found in the smallest class. This so-called inverse J–shaped distribution is an indication of healthy population structure in which recruitment rates are higher than mortality (Sop et al., 2011).

Both allometric equations used in this study provided similar figures. However, the equation by Ryan et al. (2011) from Mozambique provided consistently lower estimates. As this equation is calibrated for the stem biomass and not the entire above ground biomass of the tree, this makes sense. The highest median estimated for miombo (Zambia) in Chidumayo's was about 82 t/ha. These results match well with the modelled AGB based on remote sensing data supplied by Saatchi et al. (2011). Interestingly, the largest trees did not occur in the vegetation types with the highest AGB, the miombo woodlands, but in the *Baikiaea* woodlands. The *Baikiaea* woodlands are characterized by a more open canopy than the miombo woodlands and feature thick individual trees with large canopies. However, tree densities are low and there are large gaps in between the individual tree canopies, resulting in a grassy matrix in the inter-canopy area (Revermann et al., 2018). Thus, the much higher density of trees in the miombo woodlands compensates for, in the mean, smaller individuals (De Cauwer et al., 2018). The highest estimated AGB in the miombo woodlands of Zambia could be explained by the equally high density of stems per hectare as well as the presence of more individuals from the larger size classes than in Angolan miombo woodlands (Fig. 2).

Table 3: Model coefficients of the GLM with AGB (t/ha) as response variable (calculated based on the allometric equation by Chidumayo [2013]); variable importance calculated via hierarchical partitioning is given as explained variance in a percentage. Explained deviance of the model is 16.1%.

Predictor	Estimate	p-value	Proportion of variance explained (%)
Intercept	1.1652	0.136	–
Mean annual precipitation	0.0013	< 0.001	65.3
Silt content topsoil	0.0227	< 0.001	21.7
Temperature range	0.0130	0.042	8.4
Coarse fragments topsoil	–0.0205	0.046	2.8
Fire frequency	0.0622	0.002	1.7

The estimation of AGB using allometric equations comes with its own uncertainty when one considers either pantropical models that differ significantly in the estimation of AGB from regional models (see Sichone et al., unpublished) or site-specific models applied to local inventories (Mauya et al., 2014). Though the IPCC 2006 guidelines (Eggleston et al., 2006) point towards the advantages of using species-specific allometric equations. Given the absence of species-specific allometric equations, this study settled for regional ones. The allometric equations considered in this study were developed for miombo woodlands with the most frequently occurring genera, such as *Brachystegia*, *Julbernadia*, and *Cryptosepalum*. Even though the majority of sample sites were in miombo woodlands, other woodland types with a different species composition were analysed using the same allometric

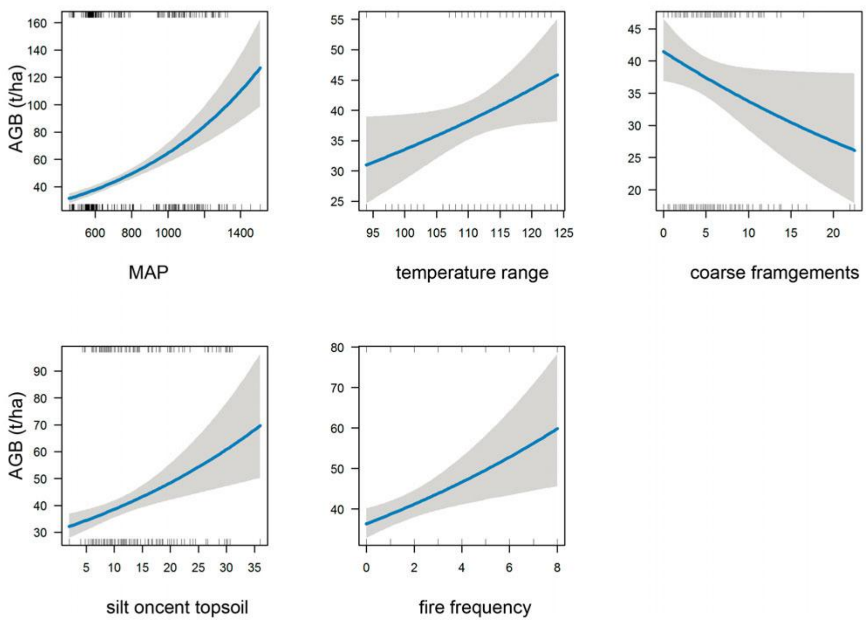

Figure 4: Visualisation of the predictor variables of the final GLM with AGB according to Chidumayo (2013). MAP = mean annual precipitation (mm); temperature range (°C); coarse fragments in the topsoil (%); silt content of the topsoil (%); fire frequency = number of fires in last 15 years.

equations in the absence of more suitable ones. Hence, it would be useful to develop equations for these woodland types to match the variability in tree biomass across all ecological zones and vegetation types. Furthermore, the inherent variability in growing conditions within a single biome such as miombo woodlands will obviously affect how well an allometric model applies to all locations in that zone. Within the geographical range of the study, there are different conditions in terms of climate, soil, and fire frequency (Tab. 1), all factors that affect allometry and thus the relationship between the independent variables and biomass.

However, new technologies currently still in the experimental stage might offer new solutions to estimate biomass on the local scale. As such, Strohbach (2018) and Knox et al. (2018) utilize unmanned aerial vehicles to investigate stand structure and height of woodlands. A study by Mathieu et al. (2018) makes use of the combination of airborne LiDAR data and freely available satellite data to calculate maps on woody cover on a regional scale. Additionally, Kankare et al. (2013) suggested the use of stem curve and crown size geometric measurements from terrestrial laser scanning data as a basis for allometric models.

Environmental drivers of AGB

On a regional scale, climate has long been identified as the main driver of vegetation patterns, and as such also of biomass. Generally, climate as the main driver was confirmed in this study, and AGB showed a positive relationship with mean annual precipitation and a negative one with mean annual temperature. Locally, however, the observed patterns of AGB deviated from this general finding. As such, miombo woodlands sampled in Angola received higher precipitation (annual mean 1123 mm) than the miombo woodlands in Zambia (annual mean 999 mm), but AGB was higher in the latter. This could be attributed in part to higher soil fertility in Zambia, represented by higher silt content in the topsoil in the GLM (Tab. 3). The share of fine material in the soil is responsible for nutrient retention, an important factor in a region where soils are predominantly sandy and very nutrient poor. Another factor could be higher antropogenic pressure on the woodlands, as population density is higher in the Angolan part of the study area than in the Zambian one (see also De Cauwer et al., 2018).

Fire can have a major impact on species composition and regeneration of woodlands. Generally, a rule of thumb indicates that fire return periods shorter than five years hinder trees from reaching mature stages that are more resistant to fire (Bond & Keeley, 2005). Thus, it is astonishing that the GLM indicated a weak but positive relationship between the number of fires and AGB. Maps of spatial and temporal patterns of fire in southern Africa (Röder et al., 2018) reveal that fire frequency does not follow a continuous gradient that can be explained purely by environmental factors. Instead, fire is controlled by human management or the lack thereof. As such, there is a clear difference in fire frequency among the *Baikiaea* woodlands. This woodland type occurs both in southeastern Angola and in northern Namibia. In northern Namibia fire frequency is low compared to the areas to the north across the Okavango River in Cuando Cubango Province in Angola, where fire frequencies were among the highest in southern Africa (Röder et al., 2018).

Because of increased canopy closure, miombo woodlands exhibit a higher fire resistance. Fire is used for multiple purposes by humans, however, such as for the preparation of fields in shifting agriculture. Furthermore, many grasslands of the miombo region burn annually (Stellmes et al., 2013). Thus, vegetation plots in the miombo region situated close to the woodland edge can be erroneously identified as having a high fire frequency as a result of a mixed pixel problem. In conclusion, high fire frequency and fire season are not suitable variables to explain AGB on a regional scale. As other studies have shown, frequent fires can convert woodlands to long-term stable grasslands or shrublands.

This underlines that AGB patterns on this regional scale cannot be explained by environmental predictors alone. Instead, anthropogenic factors (e.g., the use of woodlands for shifting cultivation, charcoal production, or timber extraction) have a long-lasting impact on the species composition and structure of the woodland, and as such on AGB. The index used for human impact in this study did not turn out to be an important predictor variable, however, and did not remain in the final model after variable selection.

This might also explain the high variability of AGB on the local scale: the estimates of AGB per vegetation type showed a high MAD, which was almost as high as the median. This high spatial variability at the local scale makes generalization about drivers of the AGB difficult and is responsible for the low model performance of the GLM.

Still, it also needs to be pointed out that the environmental data used in the modelling exercise were derived from global datasets and were not measured at the site scale by in situ measurements. The soil data, regionalized using predictive modelling approaches and various environmental data layers as explanatory variables, are particularly prone to errors.

Conclusion

This study provides a contribution to the estimates of the above-ground biomass of the woodlands in the Zambezian Phytoregion, where studies based on in situ data on a regional scale are very scarce. The most powerful variable explaining the spatial pattern of AGB was mean annual precipitation. However, models using environmental variables failed to fully explain the pattern observed in woodlands of the region. The reasons are most likely twofold. First, there is high local variability as a result of environmental heterogeneity that is not captured by the regional or global data layers used. Second, the woodlands are strongly affected and shaped by anthropogenic activities such as shifting cultivation, charcoal production, and the (unintended) use of fire.

To come to a better understanding of spatial patterns of AGB in southern African woodlands, we reiterate the importance of improving ground-based monitoring networks that will feed into the calibration and validation of remotely sensed data. Robust, standardised networks of field monitoring sites to complement global satellite observations are still insufficient. Long-term in situ monitoring is needed to investigate growth

Forest resources

rates to establish sustainable harvesting schemes for timber. Furthermore, they give insights into the regeneration capacity of the woodlands after clearing for agriculture or charcoal production.

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References

Ben-Shahar, R. (1998) Changes in structure of savanna woodlands in northern Botswana following the impacts of elephants and fire. *Plant Ecology*, **136**, 189–194.

Bodart, C., Brink, A.B., Donnay, F., Lupi, A., Mayaux, P. & Achard, F. (2013) Continental estimates of forest cover and forest cover changes in the dry ecosystems of Africa between 1990 and 2000. *Journal of Biogeography*, **40**, 1036–1047.

Bond, W.J. & Keeley, J.E. (2005) Fire as a global "herbivore": the ecology and evolution of flammable ecosystems. *Trends in Ecology and Evolution*, **20**, 387–394.

Brown, S. (1997) *Estimating biomass and biomass change of tropical forests.*FAO, Rome.

Burke, A., Juola, V., Korhonen, K., Selaniemmi, T. & Chakanga, M. (2001) *Field instructions for the NFI*. Windhoek, Namibia.

Carreiras, J.M.B., Melo, J.B. & Vasconcelos, M.J. (2013) Estimating the above-ground biomass in miombo savanna woodlands (Mozambique, East Africa) using L-band synthetic aperture radar data. *Remote Sensing*, **5**, 1524–1548.

Chave, J., Andalo, C., Brown, S. et al. (2005) Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, **145**, 87–99.

Chave, J., Réjou-Méchain, M., Búrquez, A. et al. (2014) Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, **20**, 3177–3190.

Chidumayo, E. (2013) Estimating tree biomass and changes in root biomass following clear-cutting of *Brachystegia-Julbernardia* (miombo) woodland in central Zambia. *Environmental Conservation*, **41**, 54-63.

Chidumayo, E.N. (1997) *Miombo ecology and management: an introduction.* IT Publications in association with the Stockholm Environment Institute, London, UK.

Chidumayo, E.N. & Gumbo, D.J. (2010) *The dry forests and woodlands of Africa*. Center for International Forestry Research, Gateshead, UK.

Ciais, P., Bombelli, A., Williams, M., Piao, S.L., Chave, J., Ryan, C.M., Henry, M., Brender, P. & Valentini, R. (2011) The carbon balance of Africa: synthesis of recent research studies. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **369**, 2038–2057.

De Cauwer, V., Geldenhuys, C.J., Aerts, R., Kabajani, M. & Muys, B. (2016) Patterns of forest composition and their long-term environmental drivers in the tropical dry forest transition zone of southern Africa. *Forest Ecosystems*, **3**, 3–23.

De Cauwer, V., Knox, N., Kobue-Lekalake, R., Lepetu, J.P., Matenanga, O., Naidoo, S., Nott, A., Parduhn, D., Sichone, P., Tshwenyane, S., Yeboah, E. & Revermann, R. (2018) Woodland resources and management in southern Africa. This volume.

Dewees, P.A., Campbell, B.M., Katerere, Y., Sitoe, A., Cunningham, A.B., Angelsen, A. & Wunder, S. (2010) Managing the miombo woodlands of southern Africa: policies, incentives and options for the rural poor. *Journal of Natural Resources Policy Research*, **2**, 57–73.

Dormann, C.F., Elith, J., Bacher, S. et al. (2013) Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. *Ecography*, **36**, 027–046.

Eggleston, S., Buendia, I., Miwa, K., Ngara, T. & Tanabe, K. (2006) *IPCC guidelines for national greenhouse gas inventories*. Institute for Global Environmental Strategies, Kanagawa, Japan.

Ferreira de Lima, A.R., Ferreira Batista, J.L. & Prado, I.P. (2014) Modeling tree diameter distributions in natural forests: an evaluation of 10 statistical models. *Forest Science*, **60**, 1–8.

Frost, P.G.H. (1996) *The ecology of miombo woodlands*. Centre for International Forest Research (CIFOR), Bogor, Indonesia.

Halperin, J., Lemay, V., Chidumayo, E., Verchot, L. & Marshall, P. (2016) Model-based estimation of above-ground biomass in the miombo ecoregion of Zambia. *Forest Ecosystems*, **3**, 14.

Hengl, T., Mendes de Jesus, J., Heuvelink, G.B.M. et al. (2017) SoilGrids250m: global gridded soil information based on machine learning. *PLoS one*, **12**, e0169748.

Kankare, V., Holopainen, M., Vastaranta, M., Puttonen, E., Yu, X., Hyyppä, J., Vaaja, M., Hyyppä, H. & Alho, P. (2013) Individual tree biomass estimation using terrestrial laser scanning. *ISPRS Journal of Photogrammetry and Remote Sensing*, **75**, 64–75.

Karger, D.N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R.W., Zimmermann, N.E., Linder, H.P. & Kessler, M. (2017) Climatologies at high resolution for the earth's land surface areas. *Scientific Data*, **4**, 1–20.

Knox, N.M., Strohbach, B.J. & De Cauwer, V. (2018) Potential use of 3D-derived products generated from unmanned aerial vehicle (UAV) imagery for monitoring forest degradation and woodland structure changes in the Namibian dry woodlands. This volume.

Mate, R., Johansson, T. & Sitoe, A. (2014) Biomass equations for tropical forest tree species in Mozambique. *Forests*, **5**, 535–556.

Mathieu, R., Wessels, K., Main, R., Naidoo, L., van der Bergh, F. & Erasmus, B. (2018) A radar- and LiDAR-based Earth Observation system for monitoring savannah woody structure in southern Africa. This volume.

Mauya, E.W., Mugasha, W.A., Zahabu, E., Bollandsås, O.M. & Eid, T. (2014) Models for estimation of tree volume in the miombo woodlands of Tanzania. *Southern Forests*, **76**, 209–219.

Mwakalukwa, E.E., Meilby, H. & Treue, T. (2014) Volume and aboveground biomass models for dry miombo woodland in Tanzania. *International Journal of Forestry Research*, **2014**, 1–11.

Revermann, R., Gomes, A.L., Gonçalves, F.M., Wallenfang, J., Hoche, T., Jürgens, N. & Finckh, M. (2016) Vegetation Database of the Okavango Basin. *Phytocoenologia*, **46**, 103–104.

Revermann, R., Oldeland, J., Gonçalves, F.M., Luther-Mosebach, J., Gomes, A.L., Jürgens, N. & Finckh, M. (2018) Dry tropical forests and woodlands of the Cubango Basin in southern Africa — a first classification and assessment of their woody species diversity. *Phytocoenologia*, **48**, 23–50.

Röder, A., Stellmes, M., Frantz, D. & Hill, J. (2018) Remote sensing–based environmental assessment and monitoring — generation of operational baseline and enhanced experimental products in southern Africa. This volume.

Ryan, C.M., Williams, M. & Grace, J. (2011) Above- and belowground carbon stocks in a Miombo woodland landscape of Mozambique. *Biotropica*, **43**, 423–432.

Saatchi, S.S., Harris, N.L., Brown, S., Lefsky, M., Mitchard, E.T., Sala, W., Zutta, B.R., Buermann, W., Lewis, S.L., Hagen, S., White, L., Silman, M. & Morel, A. (2011) *Benchmark for success. Proceeding in the National Academy of Sciences of the United States of America*, **108**, pp. 9899–9904.

Sop, T.K., Oldeland, J., Schmiedel, U., Ouedraogo, I. & Thiombiano, A. (2011) Population structure of three woody species in four ethnic domains of the sub-Sahel of Burkina Faso. *Land Degradation and Development*, **22**, 519–529.

Stellmes, M., Frantz, D., Finckh, M. & Revermann, R. (2013) Fire frequency, fire seasonality and fire intensity within the Okavango region derived from MODIS fire products. *Biodiversity and Ecology*, **5**, 351–362.

Strohbach (2018) Determining the degree of deforestation in the Omusati Region, northern Namibia, with the aid of drone imagery. This volume.

Tewari, V.P. (2016) Forest inventory, assessment, and monitoring, and long-term forest observational studies, with special reference to India. *Forest Science and Technology*, **12**, 24–32.

Thompson, I., Ferreira, J., Gardner, T., Guariguata, M. & Koh, L.P. (2012) Forest biodiversity, carbon and other ecosystem services: relationships and impacts of deforestation and forest degradation. *Understanding relationships between biodiversity, carbon, forests and people: the key to achieving REDD+ objectives* (ed. by K. Okabe), pp. 21–50, International Union of Forest Research Organizations (IUFRO), Vienna, Austria.

Vermeulen, S. (1996) Cutting of trees by local residents in a communal area and an adjacent state forest in Zimbabwe. *Forest Ecology and Management*, **81**, 101–111.

Wallenfang, J., Finckh, M., Oldeland, J. & Revermann, R. (2015) Impact of shifting cultivation on dense tropical woodlands in southeast Angola. *Tropical Conservation Science*, **8**, 863–892.

White, F. (1983) *The Vegetation of Africa - A descriptive memoir to accompany the Unesco/AETFAT/UNSO vegetation map of Africa*. United Nations Educational Scientific and Cultural Organisation, Paris.

References [CrossRef]

Ben-Shahar, R. (1998) Changes in structure of savanna woodlands in northern Botswana following the impacts of elephants and fire. *Plant Ecology*, **136**, 189–194. CrossRef

Bodart, C., Brink, A.B., Donnay, F., Lupi, A., Mayaux, P. & Achard, F. (2013) Continental estimates of forest cover and forest cover changes in the dry ecosystems of Africa between 1990 and 2000. *Journal of Biogeography*, **40**, 1036–1047. CrossRef

Bond, W.J. & Keeley, J.E. (2005) Fire as a global "herbivore": the ecology and evolution of flammable ecosystems. *Trends in Ecology and Evolution*, **20**, 387–394. CrossRef

Brown, S. (1997) *Estimating biomass and biomass change of tropical forests*.FAO, Rome.

Burke, A., Juola, V., Korhonen, K., Selaniemmi, T. & Chakanga, M. (2001) *Field instructions for the NFI*. Windhoek, Namibia.

Carreiras, J.M.B., Melo, J.B. & Vasconcelos, M.J. (2013) Estimating the above-ground biomass in miombo savanna woodlands (Mozambique, East Africa) using L-band synthetic aperture radar data. *Remote Sensing*, **5**, 1524–1548. CrossRef

Chave, J., Andalo, C., Brown, S. et al. (2005) Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, **145**, 87–99. CrossRef

Chave, J., Réjou-Méchain, M., Búrquez, A. et al. (2014) Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, **20**, 3177–3190. CrossRef

Chidumayo, E. (2013) Estimating tree biomass and changes in root biomass following clear-cutting of *Brachystegia-Julbernardia* (miombo) woodland in central Zambia. *Environmental Conservation*, **41**, 54-63. CrossRef

Chidumayo, E.N. (1997) *Miombo ecology and management: an introduction.* IT Publications in association with the Stockholm Environment Institute, London, UK.

Chidumayo, E.N. & Gumbo, D.J. (2010) *The dry forests and woodlands of Africa*. Center for International Forestry Research, Gateshead, UK.

Ciais, P., Bombelli, A., Williams, M., Piao, S.L., Chave, J., Ryan, C.M., Henry, M., Brender, P. & Valentini, R. (2011) The carbon balance of Africa: synthesis of recent research studies. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **369**, 2038–2057. CrossRef

De Cauwer, V., Geldenhuys, C.J., Aerts, R., Kabajani, M. & Muys, B. (2016) Patterns of forest composition and their long-term environmental drivers in the tropical dry forest transition zone of southern Africa. *Forest Ecosystems*, **3**, 3–23. CrossRef

De Cauwer, V., Knox, N., Kobue-Lekalake, R., Lepetu, J.P., Matenanga, O., Naidoo, S., Nott, A., Parduhn, D., Sichone, P., Tshwenyane, S., Yeboah, E. & Revermann, R. (2018) Woodland resources and management in southern Africa. This volume. CrossRef

Dewees, P.A., Campbell, B.M., Katerere, Y., Sitoe, A., Cunningham, A.B., Angelsen, A. & Wunder, S. (2010) Managing the miombo woodlands of southern Africa: policies, incentives and options for the rural poor. *Journal of Natural Resources Policy Research*, **2**, 57–73. CrossRef

Dormann, C.F., Elith, J., Bacher, S. et al. (2013) Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. *Ecography*, **36**, 027–046. CrossRef

Eggleston, S., Buendia, I., Miwa, K., Ngara, T. & Tanabe, K. (2006) *IPCC guidelines for national greenhouse gas inventories*. Institute for Global Environmental Strategies, Kanagawa, Japan.

Ferreira de Lima, A.R., Ferreira Batista, J.L. & Prado, I.P. (2014) Modeling tree diameter distributions in natural forests: an evaluation of 10 statistical models. *Forest Science*, **60**, 1–8.

Frost, P.G.H. (1996) *The ecology of miombo woodlands*. Centre for International Forest Research (CIFOR), Bogor, Indonesia.

Halperin, J., Lemay, V., Chidumayo, E., Verchot, L. & Marshall, P. (2016) Model-based estimation of above-ground biomass in the miombo ecoregion of Zambia. *Forest Ecosystems*, **3**, 14. CrossRef

Hengl, T., Mendes de Jesus, J., Heuvelink, G.B.M. et al. (2017) SoilGrids250m: global gridded soil information based on machine learning. *PLoS one*, **12**, e0169748. CrossRef

Kankare, V., Holopainen, M., Vastaranta, M., Puttonen, E., Yu, X., Hyyppä, J., Vaaja, M., Hyyppä, H. & Alho, P. (2013) Individual tree biomass estimation using terrestrial laser scanning. *ISPRS Journal of Photogrammetry and Remote Sensing*, **75**, 64–75. CrossRef

Karger, D.N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R.W., Zimmermann, N.E., Linder, H.P. & Kessler, M. (2017) Climatologies at high resolution for the earth's land surface areas. *Scientific Data*, **4**, 1–20. CrossRef

Knox, N.M., Strohbach, B.J. & De Cauwer, V. (2018) Potential use of 3D-derived products generated from unmanned aerial vehicle (UAV) imagery for monitoring forest degradation and woodland structure changes in the Namibian dry woodlands. This volume. CrossRef

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Mathieu, R., Wessels, K., Main, R., Naidoo, L., van der Bergh, F. & Erasmus, B. (2018) A radar- and LiDAR-based Earth Observation system for monitoring savannah woody structure in southern Africa. This volume. CrossRef

Mauya, E.W., Mugasha, W.A., Zahabu, E., Bollandsås, O.M. & Eid, T. (2014) Models for estimation of tree volume in the miombo woodlands of Tanzania. *Southern Forests*, **76**, 209–219. CrossRef

Mwakalukwa, E.E., Meilby, H. & Treue, T. (2014) Volume and aboveground biomass models for dry miombo woodland in Tanzania. *International Journal of Forestry Research*, **2014**, 1–11. CrossRef

Revermann, R., Gomes, A.L., Gonçalves, F.M., Wallenfang, J., Hoche, T., Jürgens, N. & Finckh, M. (2016) Vegetation Database of the Okavango Basin. *Phytocoenologia*, **46**, 103–104. CrossRef

Revermann, R., Oldeland, J., Gonçalves, F.M., Luther-Mosebach, J., Gomes, A.L., Jürgens, N. & Finckh, M. (2018) Dry tropical forests and woodlands of the Cubango Basin in southern Africa — a first classification and assessment of their woody species diversity. *Phytocoenologia*, **48**, 23–50. CrossRef

Röder, A., Stellmes, M., Frantz, D. & Hill, J. (2018) Remote sensing–based environmental assessment and monitoring — generation of operational baseline and enhanced experimental products in southern Africa. This volume. CrossRef

Ryan, C.M., Williams, M. & Grace, J. (2011) Above- and belowground carbon stocks in a Miombo woodland landscape of Mozambique. *Biotropica*, **43**, 423–432. CrossRef

Saatchi, S.S., Harris, N.L., Brown, S., Lefsky, M., Mitchard, E.T., Sala, W., Zutta, B.R., Buermann, W., Lewis, S.L., Hagen, S., White, L., Silman, M. & Morel, A. (2011) *Benchmark for success. Proceeding in the National Academy of Sciences of the United States of America*, **108**, pp. 9899–9904. CrossRef

Sop, T.K., Oldeland, J., Schmiedel, U., Ouedraogo, I. & Thiombiano, A. (2011) Population structure of three woody species in four ethnic domains of the sub-Sahel of Burkina Faso. *Land Degradation and Development*, **22**, 519–529. CrossRef

Stellmes, M., Frantz, D., Finckh, M. & Revermann, R. (2013) Fire frequency, fire seasonality and fire intensity within the Okavango region derived from MODIS fire products. *Biodiversity and Ecology*, **5**, 351–362. CrossRef

Strohbach (2018) Determining the degree of deforestation in the Omusati Region, northern Namibia, with the aid of drone imagery. This volume. CrossRef

Tewari, V.P. (2016) Forest inventory, assessment, and monitoring, and long-term forest observational studies, with special reference to India. *Forest Science and Technology*, **12**, 24–32. CrossRef

Thompson, I., Ferreira, J., Gardner, T., Guariguata, M. & Koh, L.P. (2012) Forest biodiversity, carbon and other ecosystem services: relationships and impacts of deforestation and forest degradation. *Understanding relationships between biodiversity, carbon, forests and people: the key to achieving REDD+ objectives* (ed. by K. Okabe), pp. 21–50, International Union of Forest Research Organizations (IUFRO), Vienna, Austria.

Vermeulen, S. (1996) Cutting of trees by local residents in a communal area and an adjacent state forest in Zimbabwe. *Forest Ecology and Management*, **81**, 101–111. CrossRef

Wallenfang, J., Finckh, M., Oldeland, J. & Revermann, R. (2015) Impact of shifting cultivation on dense tropical woodlands in southeast Angola. *Tropical Conservation Science*, **8**, 863–892. CrossRef

White, F. (1983) *The Vegetation of Africa - A descriptive memoir to accompany the Unesco/AETFAT/UNSO vegetation map of Africa*. United Nations Educational Scientific and Cultural Organisation, Paris.

Forest resources

Seeing deforestation in Zambia – On the discrepancy between biophysical land-use changes and social perception

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Abstract: Zambia has been losing about 250,000 ha of forest annually. The actors said to be responsible for this trend include charcoal producers and shifting cultivators. This widely shared understanding is flawed, however, and instead reflects a Zambian way of 'seeing deforestation', which is introduced in this paper. This paper shows, through the combination of ethnography and remote sensing, that deforestation detected from afar does not necessarily reflect local perceptions, a phenomenon that has fundamental implications for the way forest loss is addressed in Zambia.

Resumo: A Zâmbia tem vindo a perder cerca de 250000 ha de floresta anualmente. Os responsáveis referidos são, entre outros, os produtores de carvão e os agricultores itinerantes. Porém, esta percepção amplamente partilhada é incorrecta, reflectindo antes uma maneira Zambiana de "ver a desflorestação", a qual é introduzida neste artigo. Este estudo mostra, através da combinação de etnografia com detecção remota, que a desflorestação detectada à distância não reflecte necessariamente as percepções locais, o que tem implicações fundamentais para a forma como a perda florestal é abordada na Zâmbia.

Introduction

The issue of deforestation has remained one of the major global challenges of the early twenty-first century. Globally, Zambia is among the most affected countries (Hansen et al., 2013), with reportedly 250,000 ha of forest lost annually (GRZ, 2011; Vinya et al., 2012; see Kamelarczyk & Smith-Hall, 2014) – although numbers vary substantially among the different sources because some sources consider only, for example, abrupt year-to-year changes (e.g., Hansen et al., 2013). In this paper, we define deforestation as long-term forest loss that may be caused by any human activity or natural phenomenon, be it a clearcut that occurs during a very short time or long-lasting degradation processes that eventually lead to a substantial loss of forest cover. The local populations of Zambia's Central Plateau have witnessed the decrease in forested land, particularly since 2011. As spaceborne sensors observe large areas at once with regular repeat frequency, they nowadays form the backbone of many environmental monitoring initiatives (such as REDD+) and are able to provide an objective source of time, location, and extent of deforested areas. Among the 197 successfully launched earth observation missions (as of December 2013; Belward & Skøien, 2015), the Landsat mission occupies the leading role for environmental monitoring (Roy et al., 2014) for a number of reasons including a spatial resolution (30 x 30 m) that is in congruence with the size of many processes on the Earth's surface, a reasonable revisit frequency (16 days), historical data availability (since 1984), and an open data policy.

While deforestation has been a widely acknowledged challenge and anthropogenic actions have been identified as a major cause of such transformations, the precise underlying practices (which are themselves indistinguishable in remote sensing imagery) have remained largely unexamined and are currently being debated (Gumbo, 2014; Kokwe, 2012; Kokwe & Mickels-Kokwe, 2012; Mwitwa et al., 2013). However, the people said to be responsible for 'indiscriminate cutting' and the ongoing 'rampant deforestation', as it is repeatedly called, are quickly presented. Researchers, farmers, forestry officers, politicians, NGO workers, and journalists all argue that charcoal producers and practitioners of shifting cultivation, locally known as *Chitemene*, are the

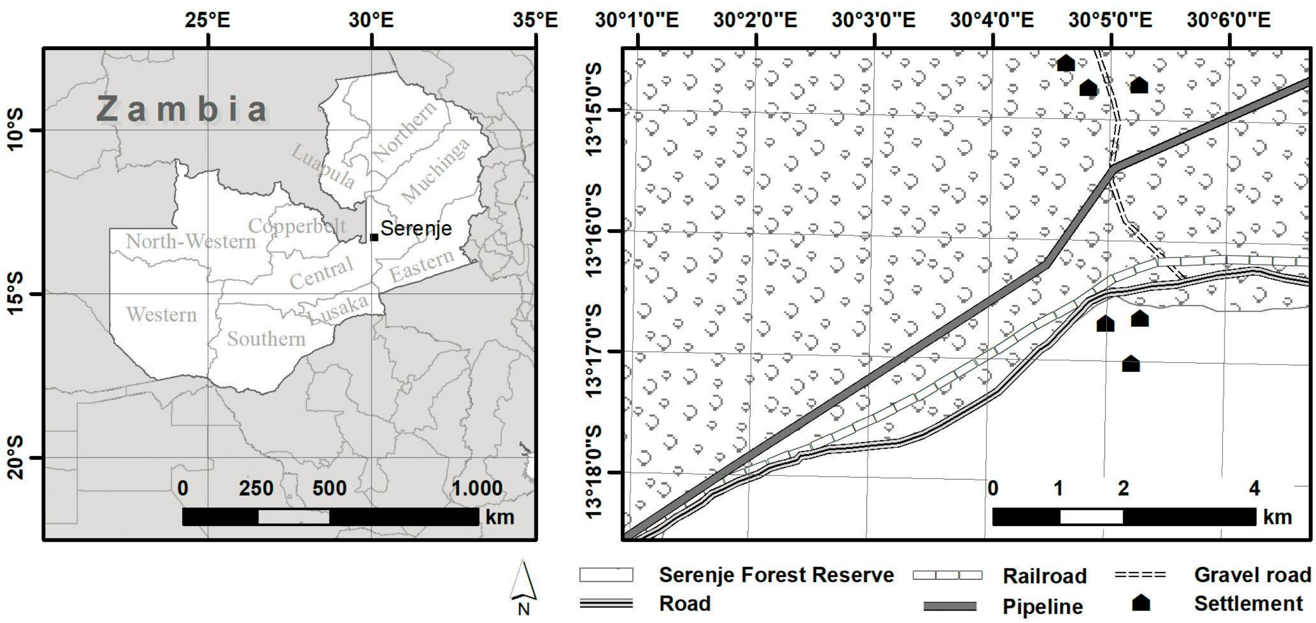

Figure 1: Study area in Central Province, Zambia.

alleged 'ignorant agents of deforestation' (Munro, 2009, p. 110). The paper at hand questions this dominant perception.

Deforestation might seem to be a rather straightforward phenomenon, one that is tangible, clearly visible, and detectable from afar. In contemporary Zambia, however, it has been conceptualized in a very particular way that is not necessarily congruent with what researchers are detecting with remote sensing data. This has crucial implications for policymakers, as the following pages will demonstrate.

Methods

Study area

To investigate local forest loss, fieldwork has been carried out on Zambia's Central Plateau in a rural community adjoining the Serenje National Forest, a protected forest reserve. The wider region, endowed with high annual rainfall (> 1000 mm/yr), is characterized by a mosaic of *Miombo* woodlands, streams, and villages, whose residents' major livelihood is subsistence and small-scale farming with a heavy emphasis on white maize.

Combining ethnography and remote sensing

The lead author spent about 12 months in 2014 and 2015 in the community mentioned above. As several practices leading to forest loss constitute a criminal offence according to, for example, the Forest Act (2015), long-term research was essential to establish rapport with various stakeholders. During fieldwork, the author applied a variety of methods well established in anthropology: he carried out a census with more than 80 different households, focus group discussions with participatory exercises, and semistructured and narrative interviews, all in addition to the constant core method, participant observation. Fieldwork was conducted not only within the village but also, amongst other places, along the highway, in marketplaces, and in a number of local, district, provincial, and national government offices across the country. This allowed for a more nuanced understanding of how local people and their conduct are embedded in and influenced by the wider political, economic, and sociocultural structures. Moreover, he undertook a review of literature, the media, and unpublished material at national research institutions.

In addition to extensive fieldwork, satellite imagery were visually analysed to bring in a complementary perspective. Frantz et al. (2016) have compiled a comprehensive Landsat dataset for the years 1984–2014 for the area under investigation (Röder et al., 2018). This preprocessing converted the at-satellite radiance to surface reflectance in order to ensure radiometric consistency across space and time as well as to ensure that the subsequent visual interpretation of land change processes was not compromised by atmospheric influences.

Satellite imagery of the study area, a sequence of Landsat images covering the research area in late May/early June (1995, 2005, 2010, 2011, 2012, 2013, 2014), is provided in Fig. 2. The black stripes originate from a sensor failure of the enhanced thematic mapper plus the onboard Landsat 7 (Markham et al., 2004) and cannot be removed reliably.

The images are displayed as false colour composites, where different parts of the electromagnetic spectrum are mapped to RGB space to visually enhance surface characteristics (red: near infrared, green: shortwave infrared, blue: red). Photosynthetically active vegetation appears in dark red, bright red tones are grasslands, and darker red tones are forests/woodlands. Blueish tones are unvegetated surfaces. As Landsat integrates the electromagnetic signal over 30 x 30 m for each pixel, spectral mixtures are apparent. For example, the amount of green/blue mixed with red indicates the density of the vegetation, where pure red denotes closed stands and intrusions of green or blue point to decreased vegetation cover.

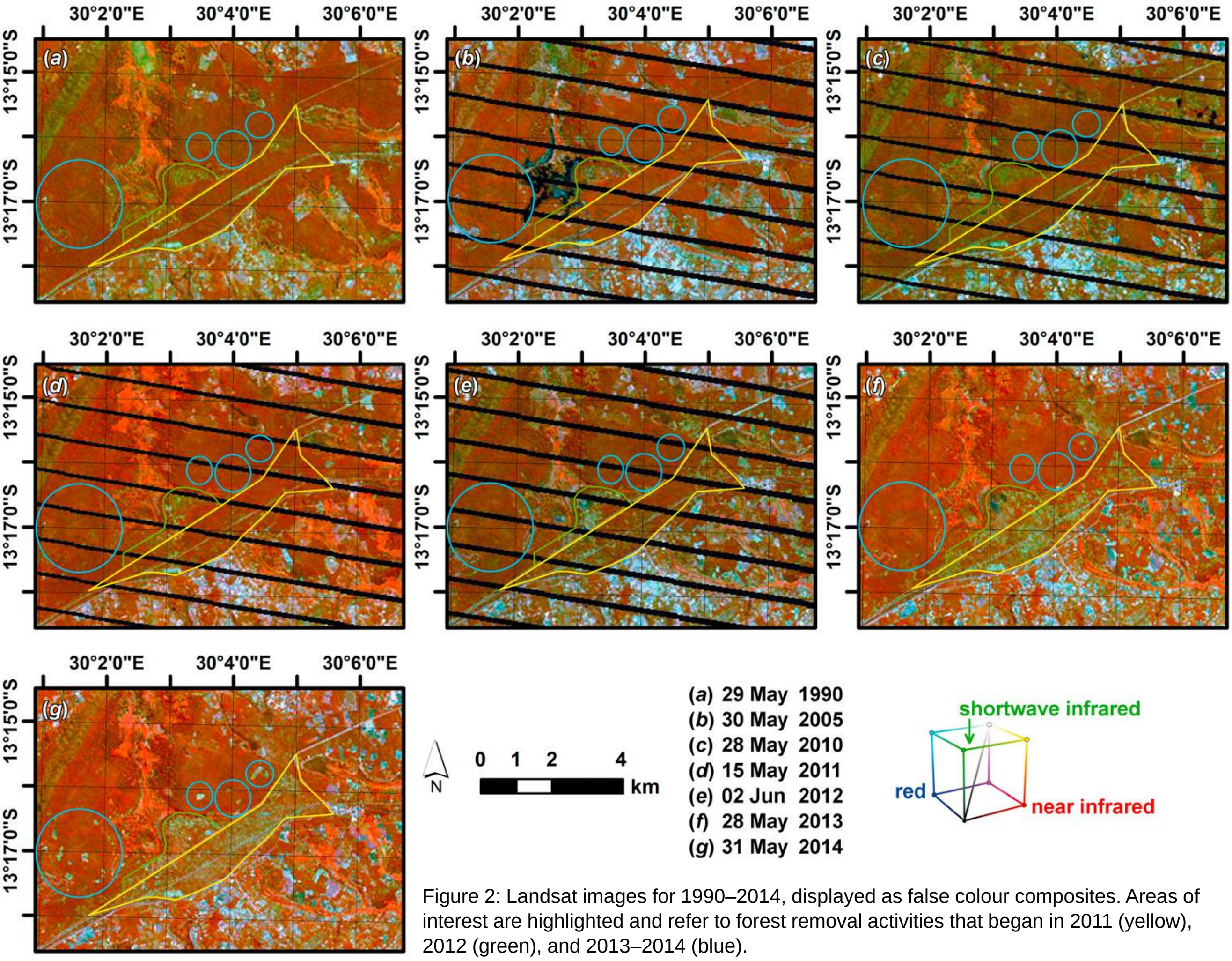

Figure 2: Landsat images for 1990–2014, displayed as false colour composites. Areas of interest are highlighted and refer to forest removal activities that began in 2011 (yellow), 2012 (green), and 2013–2014 (blue).

To demonstrate that deforestation occurs throughout the whole country, Landsat-based deforestation data from Hansen et al. (2013) were summarized for Zambia and are presented in Fig. 3. It should be noted that this dataset aimed only to detect sudden (year-to-year) stand-replacing forest loss; as such, more gradual forest loss as depicted in Fig. 2 is underrepresented and the depicted deforestation rates (in most years) are substantially lower than the often-mentioned 250,000 ha per year (see introduction). Nevertheless, a recent study by Schneibel et al. (2017) – in a similar study area in the Angolan part of the *Miombo* belt – demonstrated that gradual forest loss is not less abundant than stand-replacing losses.

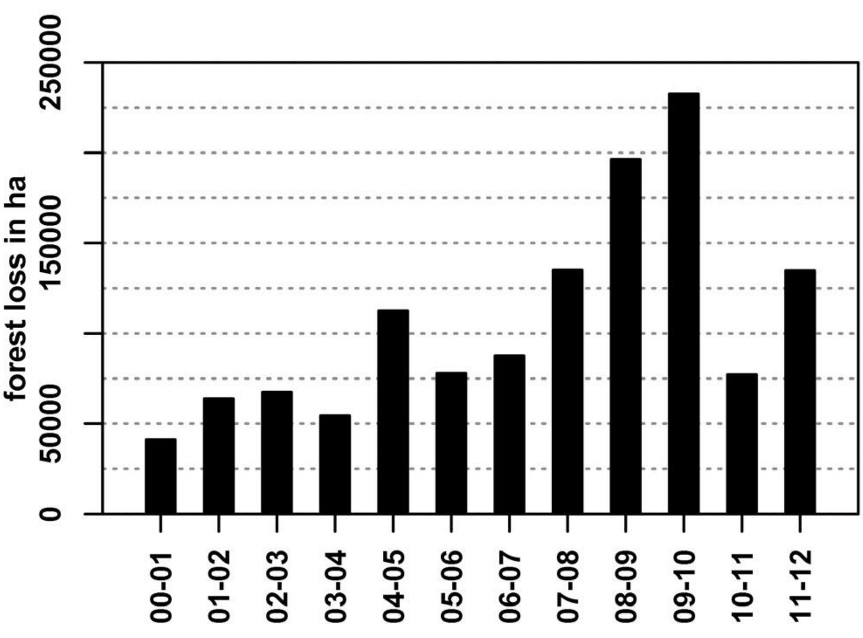

Figure 3: Stand-replacing deforestation rates for Zambia (Hansen et al., 2013).

Results

Observed forest loss

The satellite images prove that large parts of the *Miombo* were still intact in 1995, especially in the forest reserve (see Fig. 1; contiguous dark red area in Fig. 2 on imagery a). During the next 15 years, the forest extent did not change substantially, but from 2011 on, forests began to be cleared in the area between the pipeline (see Fig. 1; and yellow box in Fig. 2) and the settlement to the south. This abrupt encroachment was partly due to, first, the laying off of forest guards and paramilitaries monitoring the pipeline, and, second, an increased demand for charcoal from urban areas as a result of electricity load shedding. Since there are hardly any alternative energy sources such as gas, those households connected to the grid now resorted to charcoal for heating and especially cooking.

In 2012 areas to the north of the pipeline (south of the floodplain) were also increasingly deforested (see green box in Fig. 2). From 2013 onwards, the deforestation rate rapidly increased, and as of 2014, the only intact part of the forest reserve is east of the floodplain/north of the pipeline, although isolated patches of deforestation are already apparent there (blue circles in Fig. 2). When fieldwork was completed in late 2015, the cutting of trees had continued. This trend is apparent not only for the study area but for the whole of Zambia – and for the greater region in general. While forest loss is even higher in the Democratic Republic of the Congo, Tanzania, Mozambique, and Angola (Hansen et al., 2013), the national-scale data (Fig. 3) reveal that Zambian deforestation rates are amongst the highest in the world, and continue to increase.

Destructive practices

Stakeholders argue that charcoal producers and practitioners of shifting cultivation, locally known as *Chitemene*, are the main agents of deforestation (e.g. BBC, 2012; CIFOR, 2014; GRZ, 2010; Independent, 2016; Lusaka Voice, 2014; USAID/Zambia, 2016). Seeing bags full of charcoal lining Zambia's roads or piled in the markets will inevitably be associated with deforestation, just as local phrases for 'cutting trees' or 'losing the bush' will first and foremost evoke pictures of charcoal kilns. This biased understanding is constructed already at primary school, when charcoal burners, along with 'backward' and 'destructive' *Chitemene* farmers, are blamed during class. Even though the charcoal-deforestation nexus is not well researched in Zambia (Gumbo et al., 2013, p. 52), it nevertheless features prominently in discussions of deforestation. This view has paid the most attention to areas customarily occupied by 'the rural poor'. This, in turn, reflects the 'discourse of local blame' also observed in other deforestation contexts, which has itself been a characteristic of the strong discourse on tropical deforestation (e.g., Fairhead & Leach, 1996; Leach & Scoones, 2015; Munro, 2009; von Hellermann, 2013). While several studies on deforestation have been carried out all across Zambia, they have often only replicated the same claims (Gumbo, 2014), thus creating a widely shared consensus on the 'culprits' without regard to regional differences or the complex underlying driving forces. Fieldwork, however, has clearly revealed, first, that slash-and-burn farming hardly exists anymore in the research area and, second, that charcoal is more often than not merely produced 'opportunistically'. As such, it is a by-product of agricultural expansion and driven by massive load shedding of electricity in urban areas, especially Lusaka.

Productive and constructive practices

Yet there are a number of practices, which also entail forest loss, that are *not* perceived to be part of deforestation. When forests give way to gardens or cropland in order to feed the nation, for example, that trend is literally seen as 'productive', just as the development of open-pit mines or softwood plantations is. Equally, when trees are brought down by loggers or in the course of infrastructure developments (e.g., for the creation or expansion of roads, settlements, or power line corridors), a positive attitude prevails, as the project is 'constructive' – and 'inevitable' if one is to keep pace with those 'already ahead' within and outside of Zambia, as local residents in the research area put it.

From the perspective of the government, *legality* is a crucial factor as well: legal logging, for example, is not seen as problematic. Even more, it is represented, often implicitly, as being less harmful and even sustainable, even when occurring on an industrial scale. Accordingly, the encroachment into the Serenje National Forest was, by most villagers and employees of the district forestry office, not explicitly condemned per se, but rather seen as problematic because of its *illegality* (cf. EC, 2014, p. 34), and 'destructive' charcoal production. Seeing vast agricultural fields, which often entail the production of charcoal, however, is unlikely to trigger thoughts about deforestation, but rather admiration. When discussing Zambia's extensive private and National Farm Blocks with center-pivot irrigation and upcoming softwood plantations, both local residents and forestry officers were usually surprised by the authors' undifferentiated understanding, asking, 'But this is not deforestation, is it?!' (Fieldwork assistant, July 31, 2015, pers. comm. on Great North Road, Mkushi District). This attitude is due to the notion that when rural spaces are developed, industrialised, or urbanised, this cannot, by definition, be an example of or contribute to deforestation (cf. Munro, 2009, p. 111). In contrast to the 'destructive' cutting of trees, mechanized practices transforming the land carry the promise of development in the widest sense of the word. According to this understanding, urban load shedding that causes the increased production of charcoal for its urban consumers and forest clearing by absentee landlords for agricultural speculation hardly feature in the narratives surrounding deforestation. While urban elites, including government officials, have also encroached on Serenje National Forest, they themselves would hardly label it deforestation. Arguably, they do not do so not in order to distract from their activity, but because they do not see their 'productive' activities as part of the 'real' problems. In line with this understanding, the appropriation of land for 'productive' activities will not be labelled 'encroachment', but rather be supported by the government, which at times even interferes with the actual mission of both the Forestry Department and the parastatal environmental agency ZEMA (e.g., Chu et al., 2015; Kneen, 2013; Mickels-Kokwe & Kokwe, 2015, p. 131; cf. von Hellermann, 2013, p. 131). Moreover, opponents to such activities can be charged by the government with 'hindering development' (Miller et al., 2016), which indicates that economic growth is given priority over halting forest loss. This, in turn, has been symptomatic of the dominant discourse on deforestation, as it has evolved around the aspirations and agendas of Development (Munro, 2009, p. 114).

Summary: deforestation revisited

While all practices mentioned can be seen to have both positive and negative outcomes, there is a clear understanding of whether the cutting of trees for certain ends is actually productive or destructive, which entails corresponding moral judgements and feelings. Importantly, only practices widely and unambiguously perceived to be destructive are linked to deforestation. Thus, *deforestation* is not simply a term that describes activities involving forest loss, but rather 'an emotive notion that evokes a complexity of [specific] images and understandings' (Munro, 2009, p. 109). Deforestation, henceforth written with a capital D, is a value-laden concept bound to a set of collectively shared associations (cf. Munro, 2009, p. 109), or – as Leach & Mearns (1996) have put it more judgementally – to orthodoxies, anecdotes, assumptions, myths, and received wisdoms. This particular understanding, which is not equal to *forest loss,* means that productive or constructive practices are hardly recognized as contributing to the challenge of Deforestation, and thus receive little attention, not to mention blame, regardless of their actual impact on the forests. Arguably, productive or constructive practices are disregarded because of the dominant discourse. While the oft-quoted 250,000 hectares are the result of *all* deforesting practices, many of these are neglected in discussions of Deforestation, and, most importantly, in the interpretation of the phenomenon.

Discussion

Combating forest loss?

This dichotomy of 'good' and 'bad' practices outlined above does not just represent but also continually feeds into and thereby structures the way Deforestation is talked about and understood in Zambia (cf. Arts & Buizer, 2009, p. 342). It is not relevant whether the underlying ideas are true or false, but rather that they do exist (Arts et al., 2010, p. 58), as they are taken up and thus sustained by the media, politicians, researchers, development agencies, interpersonal communication, and educational institutions (cf. Leach & Mearns, 1996; Leach & Scoones, 2015, p. 15; Munro, 2009; van Dijk, 2003, p. 86), whether through texts or pictures, both implicitly and explicitly. This then has the power to influence behaviour and attitudes and ultimately shape policies, laws, institutional arrangements, and other discourses (Arts & Buizer, 2009, p. 341; Arts et al., 2010; Hajer, 1995; Keller, 2012; Klein, 2004). The Zambian discourse on Deforestation is therefore not just words that *describe* something, but it also has ramifications for the real world: the answer to the question 'What needs to be done to curb the high rates of Deforestation?' is obviously influenced by the discourse – 'certain types of action seem more self-evident than others' (Arts & Buizer, 2009, p. 342). Since 'productive' or 'constructive' activities, which also entail forest loss, are not acknowledged as problematic in the first place, they receive little if any attention in the fight against forest loss, even when thousands of hectares are clear-felled, which itself happens within a short period of time and renders regrowth extremely difficult and slow, if not impossible (cf. Equinox, 2005, pp. 51, 134). It should be noted that this is different from degradation caused by charcoal production only, for example (Chidumayo, August 3, 2015, pers. comm. in Makeni). Even if forested areas are to be conserved within mining or farming sites, the gross impact on biodiversity and ecosystem services is considerable (Franks & Hou-Jones, 2016). While the REDD+ projects of Zambia and many other countries are geared towards 'unsustainable' farmers and charcoal producers, other causes of large-scale forest loss remain unaddressed (Leach & Scoones, 2015). Particularly whilst large-scale farming and mining are portrayed as having a localized impact only, the production of charcoal is said to be ever-expanding country-wide. Beyond doubt, the *commercial* production of charcoal has its share in forest loss, yet if one is to comprehend – and address – Zambia's high deforestation rates, 'productive' and 'constructive' practices need to be taken into account as well. Against the background of Zambia's aspiration to become a prosperous middle-income country by 2030 (GRZ, 2011; ZDA, 2015, p. 3), however, certain practices are likely to be either deliberately or unconsciously overlooked in the future as well. In that regard, (large-scale) farming, the development of private and industrial softwood plantations, and copper mining are to take a prominent role.

In particular, this last is of tremendous importance for the national economy, providing thousands of jobs, education, and health services and being the largest taxpayer (FQM, 2016; GRZ, 2014, p. vii). Against this background, operations are likely to continue, expand further, act as a pull factor with destructive trigger effects, and be backed up by both popular opinion and the government. Importantly, the latest large-scale mines have been developed in North-Western Province – a region about 80% of which is covered by mature *Miombo* woodlands, with a low population facilitating the unopposed expansion of mines (van Alstine et al., 2011, p. 6). While a number of negative ramifications have been acknowledged in the environmental impact assessments and elsewhere (Husselman, 2008, p. 2; Mwitwa et al., 2013; Vinya et al., 2012; ZEMA et al., 2013), Deforestation is usually downplayed and ascribed to the rural poor (e.g., Equinox, 2005; FQM, 2014; FQM, 2016; KML, 2015; MMMD, 2016, pp. 42 ff.; URS, 2012). Equally, national policy documents and land use assessments mention a number of environmental threats, yet Deforestation or the loss of trees is not listed (Campbell et al., 2010, p. 22; Lindahl, 2011). Even the government's latest report on 'environmental degradation caused by mining activities' (GRZ, 2014), as well as the most recent 'environmental threats and opportunities assessment' commissioned by USAID/Zambia (2016), failed to mention the loss of trees, habitat, and biodiversity related to mines *at all*.

Conclusion

The current understanding of Deforestation in Zambia is flawed and simplistic and can be changed only if long-standing assumptions are rethought and tested on the ground. The discourse is likely to undergo change in the future, though it is usually a tardy process (Arts et al., 2010, pp. 58, 70). Researchers can contribute to this shift from both afar and nearby by investigating 'productive' and 'constructive' practices and analysing their precise impact. Moreover, urban agents and a wide range of underlying drivers such as, among others, load shedding, energy policies, governance, land rights, agricultural policies and politics need to be included in the analysis as they have all contributed to the status quo. In this regard, the monograph by Parduhn (University of Hamburg, unpubl. data), an in-depth analysis of forest loss in and around the Serenje National Forest, is one such contribution. It cautions that it is crucial for all stakeholders to understand what is meant by deforestation and what is not, to ensure that discussions start from a common understanding, based upon which reasonable and meaningful policies can be formulated. In the long term, international incentives such as REDD+ will otherwise be jeopardized as remote sensing–based forest loss rates will remain at a high level – even if 'Deforestation' practices cease altogether. 'Writing against' the dominant representation is not an easy undertaking, yet it is crucial if forests are to be protected.

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References

Arts, B., Appelstrand, M., Kleinschmit, D., Pülzl, H., Visseren-Hamakers, I.J., Eba'a Atyi, R., Enters, T., McGinley K. & Yasmi, Y. (2010) Discourses, actors and instruments in international forest governance. *Embracing complexity: meeting the challenges of international forest governance* (ed. by J. Rayner, A. Buck and P. Katila), pp. 57–73. International Union of Forest Research Organizations, Vienna.

Arts, B. & Buizer, M. (2009) Forests, discourses, institutions: a discursive-institutional analysis of global forest governance. *Forest Policy and Economics*, **11**, 340–347.

BBC (2012) Zambian forests face 'indiscriminate deforestation'. 20 June 2012. http://www.bbc.com/news/world-africa-18525049.

Belward, A.S. & Skøien, J.O. (2015) Who launched what, when and why: trends in global land-cover observation capacity from civilian earth observation satellites. *ISPRS Journal of Photogrammetry and Remote Sensing*, **103**, 115–128.

Campbell, D., Fiebig, M, Mailloux, M, Mwanza, M., Mwitwa, J. & Sieber, S. (2010) *Zambia: environmental threats and opportunities*. USAID, Washington, DC.

Chu, J., Young, K. & Phiri, D. (2015) Large-scale land acquisitions, displacement and resettlement in Zambia. Policy Brief 51. Institute for Poverty, Land and Agrarian Studies, University of the Western Cape, Cape Town.

EC – European Commission (2014) Forest governance and timber trade flows within, to and from Eastern and Southern African countries. Zambia Study. Forest Law Enforcement, Governance and Trade Study.

Equinox (2005) Lumwana Copper Project environmental impact assessment. Equinox Copper Ventures Limited. http://www.eib.org/attachments/pipeline/1570_eia_en.pdf

Fairhead, J. & Leach, M. (1996) *Misreading the African landscape: society and ecology in a forest-savanna mosaic*. Cambridge University Press, New York.

FQM – First Quantum Minerals (2014) *Environmental impact statement for the proposed Kalumbila Town Airport*.

FQM – First Quantum Minerals (2017) Balance: Weighing priorities in a responsibly managed enterprise. 2016 Sustainability Report.

Franks, P. & Hou-Jones, X. (2016) Managing trade-offs between growing food and conserving forests in sub-Saharan Africa. International Institute for Environment and Development, London.

Frantz, D., Röder, A., Stellmes, M. & Hill, J. (2016) An operational radiometric Landsat preprocessing framework for large-area time series applications. *IEEE Transactions on Geoscience and Remote Sensing*, **54**, 3928–3943.

GRZ – Government of the Republic of Zambia (2010) UN collaborative programme on REDD in developing countries. National Joint Programme Document: Zambia Quick Start Initiative. REDD-Desk Multi-Donor Trust Fund. http://theredddesk.org/sites/default/files/zambia_un-redd_njp_23_august_2010_final_4_1.pdf

GRZ – Government of the Republic of Zambia (2011) Sixth National Development Plan 2011–2015.

GRZ – Government of the Republic of Zambia (2014) Report of the Auditor General on the management of environmental degradation caused by mining activities in Zambia.

Gumbo, D. (2014) Finding a balance among charcoal, timber and livelihoods in Zambia. Centre for International Forestry Research, Bogor, Indonesia. https://www.youtube.com/watch?v=AK9Hj0z3RFY.

Gumbo, D.J., Moombe, K.B., Kandulu, M.M., Kabwe, G., Ojanen, M., Ndhlovu, E. & Sunderland, T.C. (2013) Dynamics of the charcoal and indigenous timber trade in Zambia. A scoping study in Eastern, Northern and Northwestern provinces. Occasional Paper 86. Center for International Forestry Research, Bogor, Indonesia.

Hajer, M.A. (1995) *The politics of environmental discourse: ecological modernization and the policy process*. Clarendon Press, Oxford, UK.

Hansen, M.C., Potapov, P.V., Moore, R. et al. (2013) High-resolution global maps of 21st-century forest cover change. *Science*, **342**, 850–853. Data available online from earthenginepartners.appspot.com/science-2013-global-forest.

Hou-Jones, X. & Franks, P. (2015) Food vs forests in sub-Saharan Africa: a challenge for the SDGs. International Institute for Environment and Development, London.

Husselman, M. (2008) Beekeeping in Zambia. Forest Livelihood Briefs no. 7. Center for International Forestry Research, Bogor, Indonesia.

Independent (2016) New project aims to prevent deforestation in Zambia by turning women into entrepreneurs. 6 August 2016. independent.co.uk/news/world/africa/zambia-aims-prevent-deforestation-women-charcoal-energy-environment-business-a7176291.html

Kamelarczyk, K.B. & Smith-Hall, C. (2014): REDD herring: Epistemic community control of the production, circulation and application of deforestation knowledge in Zambia. *Forest Policy and Economics*, **46**, 19–29.

Keller, R. (2012) *Doing discourse research: an introduction for social scientists*. SAGE Publications, Thousand Oaks, CA.

Klein, J. (2004) Fiddling while Madagascar burns: deforestation discourses and highland history. *Norwegian Journal of Geography*, **58**, 11–52.

KML – Kalumbila Minerals Limited (2015) The Trident Project. Sentinel Mine. Press Release. 28 August 2015. http://s1.q4cdn.com/857957299/files/doc_downloads/2015/Press-Release_Sentinel-Mine-Opening_28Aug2015.pdf

Kneen, J. (2013) Opposition builds to First Quantum Minerals' copper mine, dams, and land grab in Zambia. Mining Watch Canada. 29 November 2013. http://miningwatch.ca/blog/2013/11/29/opposition-builds-first-quantum-minerals-copper-mine-dams-and-land-grab-zambia

Kokwe, M. (2012) Forest management practices with potential for REDD+ in Zambia: Final Report. Republic of Zambia. Ministry of Lands, Natural Resources and Environmental Protection.

Leach, M. & Mearns, R. (eds.) (1996) *The lie of the land. Challenging received wisdom on the African environment*. International African Institute in association with James Currey, Oxford, UK.

Leach, M. & Scoones, I. (2015) Political ecologies of carbon in Africa. *Carbon conflicts and forest landscapes in Africa* (ed. by M. Leach and I. Scoones), pp. 1–42. Routledge, London.

Lindahl, J. (2014) Environmental impacts of mining in Zambia. Towards better environmental management and sustainable exploitation of mineral resources. Geological Survey of Sweden, Uppsala.

Lusaka Voice (2014) Zambia's alarming deforestation levels. 7 December 2014. http://lusakavoice.com/2014/12/07/zambias-alarming-deforestation-levels

Markham, B.L., Storey, J.C., Williams, D.L. & Irons, J.R. (2004) Landsat sensor performance: history and current status. *IEEE Transactions on Geoscience and Remote Sensing*, **42**, 2691–2694.

Mickels-Kokwe, G. & Kokwe, M. (2012) Forest management practices with potential for

REDD+ in Zambia. NIRAS and the Forestry Department for the UN-REDD Programme, Lusaka, Zambia.
Mickels-Kokwe, G. & Kokwe, M. (2015) Carbon projects and communities. Dynamic encounters in Zambia. *Carbon conflicts and forest landscapes in Africa* (ed. by M. Leach and I. Scoones), pp. 124–141. Routledge, London.
Miller, D., Phiri, D., Katebe, C., Kerchhoff, G., Mazeze, M. & Musongole, G. (2014) Zambian villagers 'hindering development' by resisting Canadian mining company? Institute for Poverty, Land and Agrarian Studies, University of the Western Cape, Cape Town.
MMMD – Ministry of Mines and Mineral Development (2016) Environmental and social management framework. Zambia Mining Environment Remediation and Improvement Project, Lusaka, Zambia.
Munro, Paul, G. (2009) Deforestation: Constructing problems and solutions on Sierra Leone's Freetown Peninsula. *Journal of Political Ecology*, **16**.
Mwitwa, J., Vinya, R., Kasumu, E., Syampungani, S., Monde, C. & Kasubika, R. (2013) Drivers of deforestation and potential for REDD+ interventions in Zambia. UN-REDD Zambia National Programme, Lusaka, Zambia .
Rayner, J., Buck, A. & Katila, P. (eds.) (2010) *Embracing complexity: meeting the challenges of international forest governance*. International Union of Forest Research Organizations, Vienna.
Rival, L.M. (ed.) (1998) *The social life of trees: anthropological perspectives on tree symbolism.* Berg, Oxford, UK.
Röder, A., Stellmes, M., Frantz, D. & Hill, J. (2016) Operational generation of baseline products for environmental assessment and monitoring based on optical remote sensing data. This volume.
Roy, D.P., Wulder, M.A., Loveland, T.R. et al. (2014) Landsat-8: science and product vision for terrestrial global change research. *Remote Sensing of Environment*, **145**, 154–172.
Schneibel, A., Frantz, D., Röder, A., Stellmes, M., Fischer, K., & Hill, J. (2017) Using annual Landsat time series for the detection of dry forest degradation processes in south-central Angola. Remote Sensing, **9**, 905.
URS Scott Wilson Zambia (2012) *Kansanshi Copper Smelter Project. Environmental impact statement: revised final report.* http://www.zema.org.zm/index.php/dloadspage/cat_view/40-environmental-impact-assessment-reports
USAID/Zambia (2016) Environmental threats and opportunities assessment. http://pdf.usaid.gov/pdf_docs/PA00KXCX.pdf
van Alstine, J., Ngosa, F., Manyindo, J. & Arkorful, E. (2011) *Seeking benefits and avoiding conflicts: a community-company assessment of copper mining in Solwezi, Zambia.* University of Leeds, Leeds; London School of Economics, London.
van Dijk, Teun A. (2003) The discourse-knowledge interface. *Critical discourse analysis: theory and interdisciplinarity* (ed. by G. Weiss & R. Wodak), pp. 85–109. Palgrave Macmillan, Houndsmill.
von Hellermann, P. (2013) *Things fall apart?: the political ecology of forest governance in Southern Nigeria.* Berghahn, New York.
Vinya, R., Syampungani, S., Kasumu, E., Monde, C. & Kasubika, R. (2012) *Preliminary study on the drivers of deforestation and potential for REDD+ in Zambia.* FAO, Rome.
Weiss, G. & Wodak, R. (eds.) (2003) *Critical discourse analysis: theory and interdisciplinarity.* Palgrave Macmillan, Houndsmill.
Wunder, S. (2014) Forests, livelihoods, and conservation: broadening the empirical base. *World Development*, **64**, S1–S11.
ZDA – Zambia Development Agency (2015) Zambia mining sector profile. http://www.zda.org.zm/?q=download/file/fid/16.
ZEMA, GRID-Arendal, GRID-Sioux Falls & UNEP. (2013) *Zambia: atlas of our changing environment.* ZEMA, Lusaka.

References [CrossRef]

Arts, B., Appelstrand, M., Kleinschmit, D., Pülzl, H., Visseren-Hamakers, I.J., Eba'a Atyi, R., Enters, T., McGinley K. & Yasmi, Y. (2010) Discourses, actors and instruments in international forest governance. *Embracing complexity: meeting the challenges of international forest governance* (ed. by J. Rayner, A. Buck and P. Katila), pp. 57–73. International Union of Forest Research Organizations, Vienna.

Arts, B. & Buizer, M. (2009) Forests, discourses, institutions: a discursive-institutional analysis of global forest governance. *Forest Policy and Economics*, **11**, 340–347. CrossRef

BBC (2012) Zambian forests face 'indiscriminate deforestation'. 20 June 2012. http://www.bbc.com/news/world-africa-18525049.

Belward, A.S. & Skøien, J.O. (2015) Who launched what, when and why: trends in global land-cover observation capacity from civilian earth observation satellites. *ISPRS Journal of Photogrammetry and Remote Sensing*, **103**, 115–128. CrossRef

Campbell, D., Fiebig, M, Mailloux, M, Mwanza, M., Mwitwa, J. & Sieber, S. (2010) *Zambia: environmental threats and opportunities*. USAID, Washington, DC.

Chu, J., Young, K. & Phiri, D. (2015) Large-scale land acquisitions, displacement and resettlement in Zambia. Policy Brief 51. Institute for Poverty, Land and Agrarian Studies, University of the Western Cape, Cape Town.

EC – European Commission (2014) Forest governance and timber trade flows within, to and from Eastern and Southern African countries. Zambia Study. Forest Law Enforcement, Governance and Trade Study.

Equinox (2005) Lumwana Copper Project environmental impact assessment. Equinox Copper Ventures Limited. http://www.eib.org/attachments/pipeline/1570_eia_en.pdf

Fairhead, J. & Leach, M. (1996) *Misreading the African landscape: society and ecology in a forest-savanna mosaic.* Cambridge University Press, New York. CrossRef

FQM - First Quantum Minerals (2014) *Environmental impact statement for the proposed Kalumbila Town Airport*.

FQM - First Quantum Minerals (2017) Balance: Weighing priorities in a responsibly managed enterprise. 2016 Sustainability Report.

Franks, P. & Hou-Jones, X. (2016) Managing trade-offs between growing food and conserving forests in sub-Saharan Africa. International Institute for Environment and Development, London.

Frantz, D., Röder, A., Stellmes, M. & Hill, J. (2016) An operational radiometric Landsat preprocessing framework for large-area time series applications. *IEEE Transactions on Geoscience and Remote Sensing*, **54**, 3928–3943. CrossRef

GRZ - Government of the Republic of Zambia (2010) UN collaborative programme on REDD in developing countries. National Joint Programme Document: Zambia Quick Start Initiative. REDD-Desk Multi-Donor Trust Fund. http://theredddesk.org/sites/default/files/zambia_un-redd_njp_23_august_2010_final_4_1.pdf

GRZ - Government of the Republic of Zambia (2011) Sixth National Development Plan 2011–2015.

GRZ - Government of the Republic of Zambia (2014) Report of the Auditor General on the management of environmental degradation caused by mining activities in Zambia.

Gumbo, D. (2014) Finding a balance among charcoal, timber and livelihoods in Zambia. Centre for International Forestry Research, Bogor, Indonesia. https://www.youtube.com/watch?v=AK9Hj0z3RFY.

Gumbo, D.J., Moombe, K.B., Kandulu, M.M., Kabwe, G., Ojanen, M., Ndhlovu, E. & Sunderland, T.C. (2013) Dynamics of the charcoal and indigenous timber trade in Zambia. A scoping study in Eastern, Northern and Northwestern provinces. Occasional Paper 86. Center for International Forestry Research, Bogor, Indonesia.

Hajer, M.A. (1995) *The politics of environmental discourse: ecological modernization and the policy process.* Clarendon Press, Oxford, UK.

Hansen, M.C., Potapov, P.V., Moore, R. et al. (2013) High-resolution global maps of 21st-century forest cover change. *Science*, **342**, 850–853. Data available online from earthenginepartners.appspot.com/science-2013-global-forest.

Hou-Jones, X. & Franks, P. (2015) Food vs forests in sub-Saharan Africa: a challenge for the SDGs. International Institute for Environment and Development, London.

Husselman, M. (2008) Beekeeping in Zambia. Forest Livelihood Briefs no. 7. Center for International Forestry Research, Bogor, Indonesia.

Independent (2016) New project aims to prevent deforestation in Zambia by turning women into entrepreneurs. 6 August 2016. independent.co.uk/news/world/africa/zambia-aims-prevent-deforestation-women-charcoal-energy-environment-business-a7176291.html

Kamelarczyk, K.B. & Smith-Hall, C. (2014): REDD herring: Epistemic community control of the production, circulation and application of deforestation knowledge in Zambia. *Forest Policy and Economics*, **46**, 19–29. CrossRef

Keller, R. (2012) *Doing discourse research: an introduction for social scientists.* SAGE Publications, Thousand Oaks, CA.

Klein, J. (2004) Fiddling while Madagascar burns: deforestation discourses and highland history. *Norwegian Journal of Geography*, **58**, 11–52. CrossRef

KML – Kalumbila Minerals Limited (2015) The Trident Project. Sentinel Mine. Press Release. 28 August 2015. http://s1.q4cdn.com/857957299/files/doc_downloads/2015/Press-Release_Sentinel-Mine-Opening_28Aug2015.pdf

Kneen, J. (2013) Opposition builds to First Quantum Minerals' copper mine, dams, and land grab in Zambia. Mining Watch Canada. 29 November 2013. http://miningwatch.ca/blog/2013/11/29/opposition-builds-first-quantum-minerals-copper-mine-dams-and-land-grab-zambia

Kokwe, M. (2012) Forest management practices with potential for REDD+ in Zambia: Final Report. Republic of Zambia. Ministry of Lands, Natural Resources and Environmental Protection.

Leach, M. & Mearns, R. (eds.) (1996) *The lie of the land. Challenging received wisdom on the African environment.* International African Institute in association with James Currey, Oxford, UK.

Leach, M. & Scoones, I. (2015) Political ecologies of carbon in Africa. *Carbon conflicts and forest landscapes in Africa* (ed. by M. Leach and I. Scoones), pp. 1–42. Routledge, London.

Lindahl, J. (2014) Environmental impacts of mining in Zambia. Towards better environmental management and sustainable exploitation of mineral resources. Geological Survey of Sweden, Uppsala.

Lusaka Voice (2014) Zambia's alarming deforestation levels. 7 December 2014. http://lusakavoice.com/2014/12/07/zambias-alarming-deforestation-levels

Markham, B.L., Storey, J.C., Williams, D.L. & Irons, J.R. (2004) Landsat sensor performance: history and current status. *IEEE Transactions on Geoscience and Remote Sensing*, **42**, 2691–2694. CrossRef

Mickels-Kokwe, G. & Kokwe, M. (2012) Forest management practices with potential for REDD+ in Zambia. NIRAS and the Forestry Department for the UN-REDD Programme, Lusaka, Zambia.

Mickels-Kokwe, G. & Kokwe, M. (2015) Carbon projects and communities. Dynamic encounters in Zambia. *Carbon conflicts and forest landscapes in Africa* (ed. by M. Leach and I. Scoones), pp. 124–141. Routledge, London.

Miller, D., Phiri, D., Katebe, C., Kerchhoff, G., Mazeze, M. & Musongole, G. (2014) Zambian villagers 'hindering development' by resisting Canadian mining company? Institute for Poverty, Land and Agrarian Studies, University of the Western Cape, Cape Town.

MMMD – Ministry of Mines and Mineral Development (2016) Environmental and social management framework. Zambia Mining Environment Remediation and Improvement Project, Lusaka, Zambia.

Munro, Paul, G. (2009) Deforestation: Constructing problems and solutions on Sierra Leone's Freetown Peninsula. *Journal of Political Ecology*, **16**. CrossRef

Mwitwa, J., Vinya, R., Kasumu, E., Syampungani, S., Monde, C. & Kasubika, R. (2013) Drivers of deforestation and potential for REDD+ interventions in Zambia. UN-REDD Zambia National Programme, Lusaka, Zambia .

Rayner, J., Buck, A. & Katila, P. (eds.) (2010) *Embracing complexity: meeting the challenges of international forest governance*. International Union of Forest Research Organizations, Vienna.

Rival, L.M. (ed.) (1998) *The social life of trees: anthropological perspectives on tree symbolism.* Berg, Oxford, UK.

Röder, A., Stellmes, M., Frantz, D. & Hill, J. (2016) Operational generation of baseline products for environmental assessment and monitoring based on optical remote sensing data. This volume.

Roy, D.P., Wulder, M.A., Loveland, T.R. et al. (2014) Landsat-8: science and product vision for terrestrial global change research. *Remote Sensing of Environment*, **145**, 154–172. CrossRef

Schneibel, A., Frantz, D., Röder, A., Stellmes, M., Fischer, K., & Hill, J. (2017) Using annual Landsat time series for the detection of dry forest degradation processes in south-central Angola. Remote Sensing, **9**, 905. CrossRef

URS Scott Wilson Zambia (2012) *Kansanshi Copper Smelter Project. Environmental impact statement: revised final report*. http://www.zema.org.zm/index.php/dloadspage/cat_view/40-environmental-impact-assessment-reports

USAID/Zambia (2016) Environmental threats and opportunities assessment. http://pdf.usaid.gov/pdf_docs/PA00KXCX.pdf

van Alstine, J., Ngosa, F., Manyindo, J. & Arkorful, E. (2011) *Seeking benefits and avoiding conflicts: a community-company assessment of copper mining in Solwezi, Zambia.* University of Leeds, Leeds; London School of Economics, London.

van Dijk, Teun A. (2003) The discourse-knowledge interface. *Critical discourse analysis: theory and interdisciplinarity* (ed. by G. Weiss & R. Wodak), pp. 85–109. Palgrave Macmillan, Houndsmill.

von Hellermann, P. (2013) *Things fall apart?: the political ecology of forest governance in Southern Nigeria.* Berghahn, New York.

Vinya, R., Syampungani, S., Kasumu, E., Monde, C. & Kasubika, R. (2012) *Preliminary study on the drivers of deforestation and potential for REDD+ in Zambia.* FAO, Rome.

Weiss, G. & Wodak, R. (eds.) (2003) *Critical discourse analysis: theory and interdisciplinarity.* Palgrave Macmillan, Houndsmill.

Wunder, S. (2014) Forests, livelihoods, and conservation: broadening the empirical base. *World Development*, **64**, S1–S11. CrossRef

ZDA – Zambia Development Agency (2015) Zambia mining sector profile. http://www.zda.org.zm/?q=download/file/fid/16.

ZEMA, GRID-Arendal, GRID-Sioux Falls & UNEP. (2013) *Zambia: atlas of our changing environment.* ZEMA, Lusaka.

Artificial and assisted natural regeneration of socio-economically important southern African tree species

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Abstract: Several socio-economically important indigenous tree species of southern Africa show limited natural regeneration while also being threatened by land conversion and overharvesting. Assisted tree regeneration — both artificial regeneration in nurseries and assisted natural regeneration in forests — is needed to allow the sustainable use of forest resources. Five studies of artificial and assisted natural regeneration of indigenous timber and fruit trees were performed independently from one another in Botswana, Namibia, and South Africa. They aimed to investigate and improve cultivation of seedlings, especially by testing the effects of temperature and different seed pretreatments on germination in incubators and the effects of soil inoculation with plant growth–promoting bacteria in nursery conditions. One study compared direct seeding with enrichment planting in the forest. The germination tests showed that the seeds of most indigenous species tested should be given at least six weeks to germinate, with the exception of *Bauhinia petersiana*. Seed pretreatment, especially nicking and/or soaking, can improve germination for *Strychnos cocculoides* (+17%), *Dialium englerianum* (+68%), *Erythrophleum africanum* (+22%), and *P. angolensis* (+24%). *Guibourtia coleosperma* seed germinates well without any treatment. The germination rate of *P. angolensis* seed improved (+21%) after soil inoculation with plant growth–promoting and nitrogen-fixing bacteria. The important fruit tree *Schinziophyton rautanenii* showed poor seed germination (7% to 30%), but the use of cuttings for *S. rautanenii* gave a 100% survival rate after about six months. Broadcasting seeds in the forest and covering them with soil resulted in more surviving seedlings than planting because of damage caused by rodents. Further nursery studies should focus on vegetative propagation and the optimal conditions for seedling growth and establishment of potential agroforestry tree species, while a range of assisted natural regeneration techniques remain to be tested for forests in the region.

Resumo: Diversas espécies de árvores autóctones de importância socio-económica no Sul de África demonstram uma regeneração natural limitada quando ameaçadas pela conversão de terras e sobreexploração. A regeneração assistida de árvores é necessária para permitir o uso sustentável dos recursos florestais, através da regeneração artificial em viveiros e da regeneração natural assistida em florestas. Cinco estudos sobre a regeneração artificial e natural assistida de árvores autóctones de fruto e produtoras de madeira foram realizados de forma independente uns dos outros no Botswana, Namíbia e África do Sul. O objectivo foi investigar e melhorar o cultivo de plântulas, em especial ao testar o efeito da temperatura e dos diferentes pré-tratamentos de sementes na germinação em incubadoras, e o efeito da inoculação do solo com bactérias promotoras do crescimento de plantas em condições de viveiro. Um estudo comparou sementeira directa com plantio de enriquecimento em floresta. Os testes de germinação mostraram que as sementes da maioria das espécies indígenas testadas devem ter, pelo menos, seis semanas para germinar, com excepção da *Bauhinia petersiana*. O pré-tratamento de sementes, em especial o seu corte e/ou imersão, pode melhorar a germinação de *Strychnos cocculoides* (+17%), *Dialium englerianum* (+68%), *Erythrophleum africanum* (+22%), e *P. angolensis* (+24%). As sementes de *Guibourtia coleosperma* germinam bem sem qualquer tratamento. A taxa de germinação de sementes de *P. angolensis* melhorou (+21%) após a inoculação do solo com bacterias fixadoras de azoto e promotoras do crescimento de plantas. A importante árvore de fruto *Schinziophyton rautanenii* mostrou uma baixa germinação por semente (7% a 30%), mas o uso de estacas de *S. rautanenii* resultou numa taxa de sobrevivência de 100% após cerca de seis meses. A colocação de sementes na floresta e a sua cobertura com solo resultou em mais plântulas sobreviventes que através do plantio, devido aos danos causados por roedores. Futuros estudos de viveiro deverão concentrar-se na propagação vegetativa e nas condições óptimas para o crescimento de plântulas e o estabelecimento de potenciais espécies arbóreas agroflorestais, ainda que uma série de técnicas de regeneração natural assistida continue por testar em florestas na região.

Introduction

Several socio-economically important tree species of southern Africa show limited regeneration in their natural environments. *Pterocarpus angolensis* is the most widely harvested timber tree in southern Africa (IRDNC, 2015; Von Breitenbach, 1973), as its wood, referred to as Kiaat and Mukwa in the region, is stable, easy to work, and aesthetically pleasing (ITTO, 2017) (see Figure 5 in De Cauwer et al., 2018). Forest inventories in Namibia and southern Angola show that natural regeneration is limited compared to other woody species (De Cauwer, 2016; Kabajani, 2016), similar to findings in other parts of southern Africa (Caro et al., 2005; Dirninger, 2004; von Malitz & Rathogwa, 1999). Reasons suggested for the lack of regeneration include high fire frequency, grazing and browsing pressure, climate change, and lack of light because of plant competition (Caro et al., 2005; De Cauwer, 2016; von Malitz & Rathogwa, 1999). *Baikiaea plurijuga* is another important timber tree in Zambia, Zimbabwe, and Namibia. Its wood (Zambezi teak or Mukusi) is harder than that of *P. angolensis* and is used for railway sleepers, furniture, and timber (DFSC, 2001). Limited natural regeneration in Zambia, caused by high fire frequency, bush encroachment, and seed predation by rodents, has led to the establishment of two

Figure 1: *Strychnos cocculoides* in woodland of northern Namibia (Source: V. De Cauwer, 2011).

reserves to conserve the species (DFSC, 2001; Gambiza et al., 2005). Plantations of both *B. plurijuga* and *P. angolensis* have been limited to trial plantings (Caro et al., 2005; DFSC, 2001; Piearce, 1979). There is also a high demand for the wood of *Guibourtia coleosperma* (IRDNC, 2015), traded under the generic term Rosewood and named Musivi in the region. Tree inventories in southern Angola, northern Namibia, and Zambia (De Cauwer et al., 2018) show that *G. coleosperma* is not very abundant (< 10% stems), especially not in the smaller size classes. The important fruit trees *Schinziophyton rautanenii* (Manketti, Mungongo) and *Strychnos cocculoides* (Monkey orange, Figure 1) also show limited natural regeneration in northern Namibia (Kabajani, 2016). The major reason may be overharvesting of the fruit, and for *S. rautanenii*, harvesting of the tree for its wood.

Next to limited tree regeneration, a major threat to all forests in the region is the clearing for agricultural expansion (Pröpper et al., 2010; Rudel, 2013). Many fields are left fallow for 1 up to 30 years (Chidumayo, 2002; Hilukwa, Namibia University of Science and Technology, unpubl. data). A study in northern Namibia showed that the seed density of woody species in the soil seed bank of the fallows was low (0.04 seed·m^{-2}) and that the woody species diversity of the soil seed bank was much lower than that of the above-ground vegetation, which consisted mainly of shrubs and resprouting tree species (Hilukwa, Namibia University of Science and Technology, unpubl. data). Reforestation projects in northern Namibia cannot rely on a quick natural restoration of the forest, especially when no tree root systems remain that allow coppice growth.

The harvesting of wood or fruits of indigenous tree species cannot continue in a sustainable manner if the future of the species' populations is not ensured. Programmes that support tree planting or that deliberately aim to assist natural regeneration are needed if a growing population wants to continue using forest resources. Currently, many rural inhabitants do not see the need for planting indigenous trees as they consider natural regeneration by forests and savannas to be sufficient (Gerhardt & Nemarundwe, 2006). Most trees planted in the region are exotic trees, often because national forestry extension services focused on exotic species for many decades and because knowledge on indigenous tree cultivation is lacking in the region (Erkkilä & Siiskonen, 1992; Gerhardt & Nemarundwe, 2006; Mogotsi & Ngwako, 2011). Earlier studies have shown that some miombo and *Baikiaea* woodland tree species, such as *P. angolensis, S. rautanenii, B. plurijuga, Pericopsis angolensis,* and *Julbernardia paniculata*, are difficult to grow in nurseries and that problems arise at several stages: germination, seedling survival, and seedling establishment (Chidumayo, 1992; Chimbelu, 1983; DFSC, 2001; Vander Heyden, 2014; Vermeulen, 1990; Vyamana et al., 2007). More research is needed to circumvent these difficulties, including determining the optimal physical environment for germination and seedling survival (Ministry of Agriculture, Water and Forestry, 2011) and inoculation with native bacteria and mycorrhizal fungi to improve survival and growth (Schüßler et al., 2016). Such research is especially useful for potential crop trees or trees suitable for agroforestry and would allow the propagation of individuals selected for desired tree qualities such as drought resistance, a long, straight stem for timber trees, or good fruit quality. Assisted natural regeneration is a less expensive technique for landscape restoration (Ministry of Agriculture, Water and Forestry, 2011), but is rarely used in the region. Assisted natural regeneration refers to low-cost methods that can be applied to natural forest stands to enhance natural regeneration, especially through the reduction of barriers to tree regeneration and preferably by involving local people (Ganz et al., 2003; Shono et al., 2007). These include exclusion of grazing, controlling of fire, the use of pioneer shrubs as nurse plants, the removal of plant competition, and enrichment planting (Aerts et al., 2007; Chazdon & Guariguata, 2016; Ganz et al., 2003).

Several SASSCAL projects focused on studies to facilitate artificial and assisted natural regeneration programmes of indigenous tree species. SASSCAL Task 182 focused on the collection and storage of *B. plurijuga* seeds in Zambia. SASSCAL Task 079 is monitoring thinning experiments that aim to encourage juvenile tree growth in state forests in Namibia. This article will describe five independently performed studies on germination and seedling survival of indigenous tree species performed by SASSCAL Tasks 038 and 335. The studies aimed to (1) investigate seedling germination and survival from seed and cuttings in nursery conditions, (2) test the effect of soil inoculation with plant growth–promoting bacteria on the germination of *P. angolensis* in nursery conditions, (3) investigate factors influencing germination in controlled conditions, and (4) compare direct seeding with enrichment planting in the forest.

Methods

Seedling germination and survival from seed and cuttings in nursery conditions — Botswana

The study tested the possibility of cultivating *S. rautanenii* (n = 400) and *Bauhinia petersiana* (n = 400) from seed, and for *S. rautanenii* (n = 450) from cuttings. The seed pretreatments consisted of scarification for *B. petersiana*, and removing the outer shell by cracking the nuts and soaking the kernel for 48 hours for *S. rautanenii*. Cuttings were taken from old-growth wood, young wood, and very young, pliable wood and planted in river sand. The nursery has net shading without artificial lighting. The experiment was performed from December to May 2017, with air temperatures varying between 2°C (May) and 38°C (December) and averaging 22°C. Watering was on a daily basis. Preliminary results are reported as the ratio of seeds that germinated after two months or as the ratio of cuttings that survived after six months. No statistical analysis was performed.

Soil inoculation with plant growth promoting bacteria for *P. angolensis* — Namibia

The effect of soil inoculation with plant growth–promoting and nitrogen-fixing bacteria, particularly rhizobial root nodule symbionts, on the germination of *P. angolensis* seed (n = 90) in nursery conditions was tested. In SASSCAL Task 51, wild legumes in Namibia were inspected for root nodules, and their bacterial nitrogen-fixing symbionts were isolated and characterized. A strain of the genus *Bradyrhizobium* that nodulated *P. angolensis* in sterile laboratory culture was tested on soil in Namibia. A factorial design was used with two factors: (1) inoculation/no inoculation and (2) source of the seeds (pods collected from tree or ground). All seeds were removed from the pods and scarred. The soil was a mixture of commercial potting soil with sand. Seeds were raised in pots placed in full sun during March and April with watering when the soil was dry. The average surface temperature over the 7-week experiment was 26°C, while air temperatures varied between 10°C and 29°C. Germination results were analysed using a linear regression with inoculation, source of the pods, and the interaction between the two as variables.

Factors influencing germination in controlled conditions — Namibia

The effects of temperature (26 and 30°C), and seed pretreatments (control, nicking, soaking in cold/warm/hot water, and combinations of these) on the germination of *Dialium englerianum* (n = 540), *Erythrophleum africanum* (n = 540), *G. coleosperma* (n = 540), *P. angolensis* (n = 320), and *S. rautanenii* (n = 362) were tested. All seeds were surface sterilised and placed on filter paper in sterilised petri dishes in an incubator. The seeds were monitored for a period of 14 days, after which seed viability was tested with a tetrazolium solution. Germination results were analysed with a two-way analysis of variance (ANOVA) or Kruskal-Wallis. The research design was based on the results of earlier studies (Moses, 2012; Vander Heyden, 2014), and more information can be found in Younan (2015) and De Cauwer and Younan

(2015), with the latter describing the data analysis methods.

Factors influencing germination in controlled conditions — South Africa

The effects of no (control) and five seed pretreatments on germination were compared for *S. cocculoides* (n = 180) and *G. coleosperma* (n = 180) in an incubator at a constant temperature of 25°C. The seed pretreatments consisted of soaking in cold/warm/hot water, scarification, and immersion in 32% hydrochloric acid (HCl). A blocked factorial design was used, with results reported as the ratio of seeds that germinated after 7 weeks and data analysis done through ANOVA. More details on the methodology are given in Heita (2015).

Comparison of direct seeding with enrichment planting — Namibia

Enrichment planting of nursery seedlings in a state forest in the Otjozondjupa region of Namibia (mean annual rainfall 480 mm) was compared with direct seeding for *P. angolensis, B. plurijuga,* and *G. coleosperma*. Seeds were collected near the study area; hence provenances were from the driest location possible for those species, as advised by Weber et al. (2015). A blocked factorial design was used with as treatments within the blocks and per species: (1) broadcasting of seeds (n = 180), (2) broadcasting of seeds and covering with soil (n = 180), and (3) planting of nursery-raised seedlings (n ≤ 180). Seeds of *P. angolensis* were extracted from pods and nicked, seeds of *B. plurijuga* were soaked in warm water for 24 hours, and seeds of *G. coleosperma* were not pretreated. The seedlings in the nursery were grown in 30 cm deep polyethylene bags for four months with watering every second day during the first two months decreasing to two times a week by the time of planting. The experiment was repeated in the early (January) and late (April) rainy season of 2016. Although planting at the start of the rainy season is preferable (Aerts et al., 2007), it does not guarantee that the study area will receive rain for the first months, as rainfall is limited, has a high temporal and spatial variation, and is thus unpredictable. Historical plantings showed that most planted seedlings are destroyed by browsers when all other vegetation is still dry. A small pilot project was also set up to test to what extent tree protectors can prevent small mammals from predating on the seedlings. Tree protectors were applied around 50 nursery seedlings (Fig. 2). Preliminary results are given as the ratio of seeds that germinated or as the ratio of seedlings that survived after 9 to 12 months. Statistical analysis results will be published by Chaka (Namibia University of Science and Technology, unpubl. data).

All seeds were collected in north-eastern Namibia except for study 1, which was performed with seed and cuttings from Botswana.

Figure 2: Tree protector tested around a nursery seedling (Source: M. Chaka, 2016).

Figure 3: *Schinziophyton rautanenii* plants developed from tree cuttings (Source: S. Tshwenyane, 2017).

Results

Seedling germination and survival from seed and cuttings in nursery conditions — Botswana

Seedlings of *B. petersiana* were successfully raised in the nursery with a 100% germination rate after 7 days. Germination rate of *S. rautanenii* was only 30% after 20 days. The survival rate for the cuttings was 100% for the old-wood cuttings and 80% for the young to very young-wood cuttings after 6 months, with the cuttings still growing and shooting by the end of 2017 (Fig. 3). However, no root development had taken place.

Soil inoculation with plant growth–promoting bacteria for *P. angolensis* — Namibia

The inoculation significantly ($p < 0.05$) increased the germination rate from 16% to 37% (Tab. 1). There was, however, a significant ($p < 0.05$) interaction effect between inoculation and the source of the pods: inoculation appeared to have an effect only on the germination success of seeds from pods collected from the ground. The effect of inoculation on germination time was very significant ($p < 0.0001$), with germination time decreasing from 25 to 12 days.

Table 1: Mean total germination rate and mean germination time of *Pterocarpus angolensis* seeds after 7 weeks. Treatments were soil inoculation with plant growth–promoting and nitrogen-fixing bacteria and source of the pods from which seeds were extracted.

	Germination rate (%)			Germination time (days)		
	Pods from ground	Pods from tree	TOTAL	Pods from ground	Pods from tree	TOTAL
Inoculation	50	25	37	11	13	12
No Inoculation	8	25	16	20	27	25
Total	28	25	27	12	19	16

Figure 4: *Guibourtia coleosperma* seedling germinated from broadcasted seed covered by a layer of sand (Source: M. Chaka, 2016).

Figure 5: Holes dug out by small mammals at a site where nursery seedlings were planted (Source: M. Chaka, 2016).

Factors influencing germination in controlled conditions — Namibia

Table 2 shows the germination results for temperature and seed pretreatments combined. *G. coleosperma* seed had the highest germination rate and *S. rautanenii* the lowest. The seed pretreatments showed significant effects ($p < 0.05$) only on the germination capacity of *D. englerianum*, *E. africanum*, and *P. angolensis* seed (De Cauwer & Younan, 2015), especially pretreatments that included nicking. All treatments did shorten the germination time of *G. coleosperma* by an average of 5 days compared to the control. Germination was slightly better at 26°C but this was significant only for two species and may have been caused by quicker discarding of mouldy seeds during the experiment at 30°C. A tetrazolium test showed that most nongerminated seeds were still viable after two to three weeks.

Table 2: Mean total germination rate and mean germination time of indigenous tree seeds across all treatments after 2 weeks' incubation in an incubator. The age of the seeds refers to the storage period.

	n	Age (years)	Germination (%)	Germination time (days)
Dialium englerianum	540	< 1	41	7.4
Erythrophleum africanum	540	12	20	8.0
Guibourtia coleosperma	540	3	91	7.3
Pterocarpus angolensis	320	1–2	23	6.6
Schinziophyton rautanenii	362	2–12	7	10.8

Factors influencing germination in controlled conditions — South Africa

Germination results indicated clear differences between species and certain pretreatments (Tab. 3). The treatment with HCl and scarification resulted in significantly lower ($p < 0.001$) germination rates for both species and a longer germination time for *G. coleosperma*. Seeds of both species responded best to soaking in warm water, although soaking did not significantly improve germination for *G. coleosperma* seed, which germinated well without any treatment. Maximum germination time for *G. coleosperma* was reached after six weeks, while *S. cocculoides* seeds were still germinating after seven weeks.

Table 3: Total germination rate (%) of *Strychnos cocculoides* and *Guibourtia coleosperma* seeds over a period of 7 weeks in an incubator.

	Weeks	Control	Cold water	Warm water	Hot water	HCl	Scarification
Strychnos cocculoides	**2**	0	0	0	0	0	0
	4	27	30	27	17	0	0
	6	57	47	60	23	0	3
	7	63	70	80	40	0	3
Guibourtia coleosperma	**2**	0	7	3		0	0
	4	63	73	70	60	50	57
	6	80	80	83	67	63	63
	7	80	80	83	70	67	67

Comparison of direct seeding with enrichment planting — Namibia

The preliminary results of the early rain season show that regeneration from seeds covered with a layer of soil was much better compared to that of broadcasted seeds and planted nursery seedlings. After the first nine weeks of regeneration, 60% of the covered seeds of all species combined resulted in surviving seedlings (Fig. 4) compared to 0.2% of the noncovered seeds. However, the seedling survival rate of the covered seeds started to decline afterwards. All nursery seedlings were dug out by small mammals within the first 4 weeks after planting (Fig. 5). After a period of 1 year, the seedling survival rate from seeds covered with a layer of soil was 11%, and that from noncovered seeds was 1.3%. Some 16% of the broadcasted noncovered seed were still present and intact on top of the soil.

None of the late rainy-season treatments resulted in surviving seedlings: no germinations were recorded for either direct seeding treatment, and the survival rate of the nursery seedlings after six weeks was 0% because all were destroyed by small mammals. The tree protectors were able to protect the seedlings from small mammals (Fig. 2), as all seedlings could still be observed in the tree protector after a year. However, all those seedlings had died of desiccation by the end of 2016.

Discussion

Seed pretreatment can improve germination for *S. cocculoides, D. englerianum, E. africanum,* and *P. angolensis*. Soaking *S. cocculoides* seed in water overnight increased the germination rate, with 17% after 7 weeks compared to no seed pretreatment (study 4), while the germination rate of *D. englerianum* increased 68% with nicking and soaking in water (study 3). In contrast, the seed of *E. africanum* and *P. angolensis* should only be nicked and not soaked (study 3). Seeds of most indigenous species tested need more than 2 weeks' germination time, at least 6 to 8 weeks, as there were a large number of viable, nongerminated seeds after 2 weeks in studies 2, 3, and 4. Vander Heyden (2014) observed that although germination of *P. angolensis* seeds in controlled laboratory conditions (at 26°C) started after 12 days, it continued for over a year and reached a germination rate of 47%, much higher than that obtained in studies 2 and 3, which lasted less than two months. The only species that showed a high germination rate (> 90%) within two weeks were *B. petersiana* (study 1: 7 days) and *G. coleosperma* (study 3: two weeks). It is not clear why it took *G. coleosperma* 6 weeks to reach a germination rate of 80% in study 4, especially as the seeds were two years younger than those of study 3. Probably, it is caused by a slightly lower incubator temperature and because the seeds in study 4 were thrown away as soon as they developed mould, while study 3 found that many seeds with mould still germinated.

Future studies should investigate the effect of different day lengths and temperatures on germination, especially as study 3 was not conclusive. More studies on seedling growth and establishment are especially needed (Ministry of Agriculture, Water and Forestry, 2011), for example as related to shade conditions, as performed by Graz (2003) for *S. rautanenii*. Additionally, superior genetic material should be collected to cultivate potential agroforestry or crop species with high drought tolerance and desired characteristics such as bole length or fruit yield, such as is being done for *Sclerocarya birrea* (Marula) (Gouwakinnou et al., 2011; Leakey et al., 2002). Propagation of tree species with low germination rates may be better done via tissue culture techniques (Vander Heyden, 2014) or through vegetative propagation in nursery conditions, as demonstrated for *S. rautanenii* in study 1. However, results of study 1 showed that vegetative propagation should be studied over a much longer period (> 1 year). No recent information is available on vegetative propagation of the species.

Mean germination time of *P. angolensis* in nursery conditions declined from 3.5 weeks to 12 days (study 2) when using soil inoculated with nitrogen-fixing bacteria. The results are more promising than a study by Moola et al. (2009) that tested the effects of mycorrhizae on both germination and seedling growth of *P. angolensis* and showed a beneficial effect only on growth; by contrast, this study also showed a positive effect on germination. More experiments are needed to test the use of nitrogen-fixing and other microorganisms on seedling growth of indigenous tree species. The bacteria serve various purposes including quick establishment of root nodules for nodulation of plants, enhancement of root formation, phosphate mobilisation from the soil, and a protective role via the formation of siderophores (Chimwamurombe et al., 2016; Grönemeyer et al., 2012). The use of plant growth–promoting bacteria is more environmentally friendly and sustainable compared to chemical fertilisers.

Direct seeding of woody species in natural forest is a promising propagation method if the seeds are covered by soil. The covering appears to provide protection against predation compared to the noncovered seeds. SASSCAL Task 182 also reported a high predation pressure on *B. plurijuga* seeds by various rodents in Zambia, while Fors (2002) found a high predation of broadcasted *P. angolensis* seeds in forests in Tanzania (66% in 10 days). Timing of direct seeding is crucial for the development of seedlings. Study 5 showed that only direct seeding in the early rainy season worked compared to direct seeding in the late rainy season, but this will have been influenced by the below-average rainfall of 286 mm in the study area during the rainy season of 2015/2016. Optimal is to seed at the start of a long and good rainfall period; this is an unrealistic method, however, because of the unpredictability of rainfall, especially for remote forest areas for which logistics are difficult to organise.

Figure 6: Seedlings ready for planting at the University of Agriculture and Natural Resources, Botswana (Source: S. Tshwenyane, 2014).

Figure 7: *Schinziophyton rautenenii* tree planting in the garden of the University of Agriculture and Natural Resources, Botswana (Source: S. Tshwenyane, 2014).

Enrichment planting of nursery seedlings in the forest was not successful because of predation and uprooting by small mammals unless the seedlings are protected. Hall (2008) also reported predation and/or uprooting by small mammals of 48% of planted tree seedlings within weeks of planting in a secondary forest in the Central African Republic. He demonstrated how enclosures with chicken wire increased survival of the seedlings. The tree protectors used in this experiment (Fig. 2) did provide protection but were not able to shelter the seedlings from high temperatures during the summer. A tree protector that would allow more air to flow through could be considered for potential crop trees, but planting under nurse shrubs (Aerts et al., 2007) or in between thorn shrubs may be economically more viable. Nursery plants with a large root/shoot ratio should be used, as they have a better chance of survival in the field (Weber et al., 2015).

Considering the limited results with forest seeding and planting, other assisted regeneration measures should be tested in the region, especially fire and browsing protection, forest thinning, and protection of root systems on fallow lands. Programmes to promote the cultivation of indigenous trees should focus on potential agroforestry species and include raising community awareness of the need for indigenous tree planting. Cultivation can be encouraged through demonstration plots and community nurseries (Figs. 6 and 7), as is already done in Botswana (Mogotsi & Ngwako, 2011). This approach demonstrates the potential to domesticate indigenous woody species and build the capacity of local populations in indigenous tree cultivation.

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References

Aerts, R., Negussie, A., Maes, W., November, E., Hermy, M. & Muys, B. (2007) Restoration of dry Afromontane forest using pioneer shrubs as nurse-plants for *Olea europaea* ssp. *cuspidata*. *Restoration Ecology*, **15**, 129–138.

Caro, T.M., Sungula, M., Schwartz, M.W. & Bella, E.M. (2005) Recruitment of *Pterocarpus angolensis* in the wild. *Forest Ecology and Management*, **219**, 169–175.

Chazdon, R.L. & Guariguata, M.R. (2016) Natural regeneration as a tool for large-scale forest restoration in the tropics: prospects and challenges. *Biotropica*, **48**, 716–730.

Chidumayo, E. (1992) Seedling ecology of two miombo woodland trees. *Plant Ecology*, **103**, 51–58.

Chidumayo, E.N. (2002) Changes in miombo woodland structure under different land tenure and use systems in central Zambia. *Journal of Biogeography*, **29**, 1619–1626.

Chimbelu, E.G. (1983) A germination and survival study of mugongo under laboratory and greenhouse conditions. *Indian Forester*, **November**, 804–808.

Chimwamurombe, P.M., Grönemeyer, J.L. & Reinhold-Hurek, B. (2016) Isolation and characterization of culturable seed-associated bacterial endophytes from gnotobiotically grown Marama bean seedlings. *FEMS Microbiology Ecology*, **92**.

De Cauwer, V. (2016) Autecological aspects of the African timber tree *Pterocarpus angolensis* in support of its sustainable management. PhD thesis, KU Leuven, Leuven.

De Cauwer, V., Knox, N., Kobue-Lekalake, R., Lepetu, J.P., Matenanga, O., Naidoo, S., Nott, A., Parduhn, D., Sichone, P., Tshwenyane, S., Yeboah, E. & Revermann, R. (2018) Woodland resources and management in southern Africa. This volume.

De Cauwer, V. & Younan, R. (2015) Seed germination of Namibian woodland tree species. *Dinteria*, **35**, 43–52.

DFSC (2001) *Conservation plan for genetic resources of Zambezi teak (*Baikiaea plurijuga*) in Zambia*. Danida Forest Seed Centre, Humlebaek, Denmark.

Dirninger, P. (2004) *Natural regeneration and management implications of the miombo forests in Tanzania.* I-TOO Working Paper no. 25. University of Natural Resources and Applied Sciences, Vienna.

Erkkilä, A. & Siiskonen, H. (1992) *Forestry in Namibia 1850–1990*. University of Joensuu, Faculty of Forestry, Joensuu, Finland.

Fors, L. (2002) *Tree seed survival across a miombo woodland fragmentation gradient in Tanzania*. Uppsala University, Uppsala, Sweden.

Gambiza, J., Campbell, B.M., Moe, S.R. & Frost, P.G. (2005) Fire behaviour in a semi-arid *Baikiaea plurijuga* savanna woodland on Kalahari sands in western Zimbabwe: research letter. *South African Journal of Science*, **101**, 239–244.

Ganz, D., Durst, P., Dugan, P. & Mc Kenzie, P. (2003) Assisted natural regeneration: an overview. FAO Regional Office Asia and Pacific, Bangkok.

Gerhardt, K. & Nemarundwe, N. (2006) Participatory planting and management of indigenous trees: lessons from Chivi District, Zimbabwe. *Agriculture and Human Values*, **23**, 231–243.

Gouwakinnou, G.N., Assogbadjo, A.E., Lykke, A.M. & Sinsin, B. (2011) Phenotypic variations in fruits and selection potential in *Sclerocarya birrea* subsp. *birrea*. *Scientia Horticulturae*, **129**, 777–783.

Graz, F.P. (2003) The growth of *Schinziophyton rautanenii* seedlings under different shade conditions. *Dinteria*, **28**, 44–46.

Grönemeyer, J.L., Burbano, C.S., Hurek, T. & Reinhold-Hurek, B. (2012) Isolation and characterization of root-associated bacteria from agricultural crops in the Kavango region of Namibia. *Plant and Soil*, **356**, 67–82.

Hall, J.S. (2008) Seed and seedling survival of African mahogany (*Entandrophragma* spp.) in the Central African Republic: implications for forest management. *Forest Ecology and Management*, **255**, 292–299.

Heita, H.T.N. (2015) *Propagation of indigenous species: the effects of various seed pre-treatments to improve germination in* Strychnos cocculoides *and* Guibourtia coleosperma *from Kavango West Region, Namibia.* Stellenbosch University, Stellenbosch, South Africa.

IRDNC (2015) Timber trade in Namibia. Poster. IRDNC, Windhoek.

ITTO (2017) Muninga (*Pterocarpus angolensis*). *International Tropical Timber Organization: lesser used species*. International Tropical Timber Organization, Yokohama, Japan.

Kabajani, M.W. (2016) An assessment of the natural regeneration of valuable woody species in the Kavango regions of north eastern Namibia. Master thesis, Namibia University of Science and Technology, Windhoek.

Leakey, R., Shackleton, S., du Plessis, P., Pate, K. & Lombard, C. (2002) Characterization of phenotypic variation in marula (*Sclerocarya birrea*) fruits, nuts and kernels in South Africa and Namibia. Unpublished report, James Cook University, Cairns.

Ministry of Agriculture, Water and Forestry (2011) *A forest research strategy for Namibia (2011–2015)*. Ministry of Agriculture, Water and Forestry, Windhoek, Namibia.

Mogotsi, K.K. & Ngwako, S. (2011) *Towards afforestation and livelihoods improvement: MSB-UPP contribution in Botswana*. Nairobi, Kenya. Botswana College of Agriculture, Gabarone.

Moola, S.W., Muimba-Kankolongo, A. & Kangwa, J.M. (2009) Growth performance of *Pterocarpus angolensis* seedlings in mycorrhizae colonized and uncolonized soils from high-rainfall area of Zambia. *Journal of Applied Biosciences*, **19**, 1054–1064.

Moses, R. (2012) Seed physiological aspects of large seeded species of the Kavango woodland, Namibia. BSc Honours thesis, University of Pretoria, Pretoria.

Piearce, G.D. (1979) A new vascular wilt disease and its relationship to widespread decline of *Pterocarpus angolensis* in Zambia. *Pans*, **25**, 37–45.

Pröpper, M., Gröngröft, A., Falk, T., Eschenbach, A., Fox, T., Gessner, U., Hecht, J., Hinz, M. O., Huettich, C., Hurek, T., Kangombe, F. N., Keil, M., Kirk, M., Mapaure, C., Mills, A., Mukuya, R., Namwoonde, N. E., Overmann, J., Petersen, A., Reinhold-Hurek, B., Schneiderat, U., Strohbach, B. J., Lück-Vogel, M. & Wisch, U. (2010) Causes and perspectives of land-cover change through expanding cultivation in Kavango. *Biodiversity in southern Africa. Volume 3: Implications for landuse and management* (ed. by Hoffman, M. T., Schmiedel, U. & Jürgens, N.), pp. 1–31, Klaus Hess Publishers, Göttingen & Windhoek.

Rudel, T.K. (2013) The national determinants of deforestation in sub-Saharan Africa. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **368**, 20120405.

Schüßler, A., Krüger, C. & Urgiles, N. (2016) Phylogenetically diverse AM fungi from Ecuador strongly improve seedling growth of native potential crop trees. *Mycorrhiza*, **26**, 199–207.

Shono, K., Cadaweng, E.A. & Durst, P.B. (2007) Application of assisted natural regeneration to restore degraded tropical forestlands. *Restoration Ecology*, **15**, 620–626.

Vander Heyden, F. (2014) Germination experiments with the southern African tree species *Pterocarpus angolensis*: in-vivo and in-vitro. MSc Thesis, University of Ghent, Gent.

Vermeulen, W.J. (1990) *A monograph on Pterocarpus angolensis*. Department of Environment Affairs, Water Affairs, and Forestry, Pretoria.

Von Breitenbach, F. (1973) *Pterocarpus angolensis.* A monograph. Trees in South Africa. *Journal of the Tree Society of South Africa*, **XXV**.

von Malitz, G.P. & Rathogwa, H.R. (1999) Dynamics of *Pterocarpus angolensis* (kiaat) in South Africa. Natural Forests and Savanna Woodlands Symposium II, Knysna, South Africa.

Vyamana, V.G., Chamshama, S.A.O. & Mugasha, A.G. (2007) Effect of nursery practices on seedling survival and growth of selected miombo tree species, Morogoro, Tanzania. *Discovery and Innovation*, **19**, 122–138.

Weber, J.C., Montes, C.S., Kalinganire, A., Abasse, T. & Larwanou, M. (2015) Genetic variation and clines in growth and survival of *Prosopis africana* from Burkina Faso and Niger: comparing results and conclusions from a nursery test and a long-term field test in Niger. *Euphytica*, **205**, 809–821.

Younan, R. (2015) *Germination experiment. Final report.* SASSCAL, Windhoek.

References [CrossRef]

Aerts, R., Negussie, A., Maes, W., November, E., Hermy, M. & Muys, B. (2007) Restoration of dry Afromontane forest using pioneer shrubs as nurse-plants for *Olea europaea* ssp. *cuspidata*. *Restoration Ecology*, **15**, 129–138. CrossRef

Caro, T.M., Sungula, M., Schwartz, M.W. & Bella, E.M. (2005) Recruitment of *Pterocarpus angolensis* in the wild. *Forest Ecology and Management*, **219**, 169–175. CrossRef

Chazdon, R.L. & Guariguata, M.R. (2016) Natural regeneration as a tool for large-scale forest restoration in the tropics: prospects and challenges. *Biotropica*, **48**, 716–730. CrossRef

Chidumayo, E. (1992) Seedling ecology of two miombo woodland trees. *Plant Ecology*, **103**, 51–58. CrossRef

Chidumayo, E.N. (2002) Changes in miombo woodland structure under different land tenure and use systems in central Zambia. *Journal of Biogeography*, **29**, 1619–1626.

Chimbelu, E.G. (1983) A germination and survival study of mugongo under laboratory and greenhouse conditions. *Indian Forester*, **November**, 804–808.

Chimwamurombe, P.M., Grönemeyer, J.L. & Reinhold-Hurek, B. (2016) Isolation and characterization of culturable seed-associated bacterial endophytes from gnotobiotically grown Marama bean seedlings. *FEMS Microbiology Ecology*, **92**. CrossRef

De Cauwer, V. (2016) Autecological aspects of the African timber tree *Pterocarpus angolensis* in support of its sustainable management. PhD thesis, KU Leuven, Leuven.

De Cauwer, V., Knox, N., Kobue-Lekalake, R., Lepetu, J.P., Matenanga, O., Naidoo, S., Nott, A., Parduhn, D., Sichone, P., Tshwenyane, S., Yeboah, E. & Revermann, R. (2018) Woodland resources and management in southern Africa. This volume. CrossRef

De Cauwer, V. & Younan, R. (2015) Seed germination of Namibian woodland tree species. *Dinteria*, **35**, 43–52.

DFSC (2001) *Conservation plan for genetic resources of Zambezi teak (*Baikiaea plurijuga*) in Zambia*. Danida Forest Seed Centre, Humlebaek, Denmark.

Dirninger, P. (2004) *Natural regeneration and management implications of the miombo forests in Tanzania*. I-TOO Working Paper no. 25. University of Natural Resources and Applied Sciences, Vienna.

Erkkilä, A. & Siiskonen, H. (1992) *Forestry in Namibia 1850–1990*. University of Joensuu, Faculty of Forestry, Joensuu, Finland.

Fors, L. (2002) *Tree seed survival across a miombo woodland fragmentation gradient in Tanzania*. Uppsala University, Uppsala, Sweden.

Gambiza, J., Campbell, B.M., Moe, S.R. & Frost, P.G. (2005) Fire behaviour in a semi-arid *Baikiaea plurijuga* savanna woodland on Kalahari sands in western Zimbabwe: research letter. *South African Journal of Science*, **101**, 239–244.

Ganz, D., Durst, P., Dugan, P. & Mc Kenzie, P. (2003) Assisted natural regeneration: an overview. FAO Regional Office Asia and Pacific, Bangkok.

Gerhardt, K. & Nemarundwe, N. (2006) Participatory planting and management of indigenous trees: lessons from Chivi District, Zimbabwe. *Agriculture and Human Values*, **23**, 231–243. CrossRef

Gouwakinnou, G.N., Assogbadjo, A.E., Lykke, A.M. & Sinsin, B. (2011) Phenotypic variations in fruits and selection potential in *Sclerocarya birrea* subsp. *birrea*. *Scientia Horticulturae*, **129**, 777–783. CrossRef

Graz, F.P. (2003) The growth of *Schinziophyton rautanenii* seedlings under different shade conditions. *Dinteria*, **28**, 44–46.

Grönemeyer, J.L., Burbano, C.S., Hurek, T. & Reinhold-Hurek, B. (2012) Isolation and characterization of root-associated bacteria from agricultural crops in the Kavango region of Namibia. *Plant and Soil*, **356**, 67–82. CrossRef

Hall, J.S. (2008) Seed and seedling survival of African mahogany (*Entandrophragma* spp.) in the Central African Republic: implications for forest management. *Forest Ecology and Management*, **255**, 292–299. CrossRef

Heita, H.T.N. (2015) *Propagation of indigenous species: the effects of various seed pre-treatments to improve germination in* Strychnos cocculoides *and* Guibourtia coleosperma *from Kavango West Region, Namibia.* Stellenbosch University, Stellenbosch, South Africa.

IRDNC (2015) Timber trade in Namibia. Poster. IRDNC, Windhoek.

ITTO (2017) Muninga (*Pterocarpus angolensis*). *International Tropical Timber Organization: lesser used species*. International Tropical Timber Organization, Yokohama, Japan.

Kabajani, M.W. (2016) An assessment of the natural regeneration of valuable woody species in the Kavango regions of north eastern Namibia. Master thesis, Namibia University of Science and Technology, Windhoek.

Leakey, R., Shackleton, S., du Plessis, P., Pate, K. & Lombard, C. (2002) Characterization of phenotypic variation in marula (*Sclerocarya birrea*) fruits, nuts and kernels in South Africa and Namibia. Unpublished report, James Cook University, Cairns.

Ministry of Agriculture, Water and Forestry (2011) *A forest research strategy for Namibia (2011–2015).* Ministry of Agriculture, Water and Forestry, Windhoek, Namibia.

Mogotsi, K.K. & Ngwako, S. (2011) *Towards afforestation and livelihoods improvement: MSB-UPP contribution in Botswana*. Nairobi, Kenya. Botswana College of Agriculture, Gabarone.

Moola, S.W., Muimba-Kankolongo, A. & Kangwa, J.M. (2009) Growth performance of *Pterocarpus angolensis* seedlings in mycorrhizae colonized and uncolonized soils from high-rainfall area of Zambia. *Journal of Applied Biosciences*, **19**, 1054–1064.

Moses, R. (2012) Seed physiological aspects of large seeded species of the Kavango woodland, Namibia. BSc Honours thesis, University of Pretoria, Pretoria.

Piearce, G.D. (1979) A new vascular wilt disease and its relationship to widespread decline of *Pterocarpus angolensis* in Zambia. *Pans*, **25**, 37–45.

Pröpper, M., Gröngröft, A., Falk, T., Eschenbach, A., Fox, T., Gessner, U., Hecht, J., Hinz, M. O., Huettich, C., Hurek, T., Kangombe, F. N., Keil, M., Kirk, M., Mapaure, C., Mills, A., Mukuya, R., Namwoonde, N. E., Overmann, J., Petersen, A., Reinhold-Hurek, B., Schneiderat, U., Strohbach, B. J., Lück-Vogel, M. & Wisch, U. (2010) Causes and perspectives of land-cover change through expanding cultivation in Kavango. *Biodiversity in southern Africa. Volume 3: Implications for landuse and management* (ed. by Hoffman, M. T., Schmiedel, U. & Jürgens, N.), pp. 1–31, Klaus Hess Publishers, Göttingen & Windhoek.

Rudel, T.K. (2013) The national determinants of deforestation in sub-Saharan Africa. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **368**, 20120405. CrossRef

Schüßler, A., Krüger, C. & Urgiles, N. (2016) Phylogenetically diverse AM fungi from Ecuador strongly improve seedling growth of native potential crop trees. *Mycorrhiza*, **26**, 199–207. CrossRef

Shono, K., Cadaweng, E.A. & Durst, P.B. (2007) Application of assisted natural regeneration to restore degraded tropical forestlands. *Restoration Ecology*, **15**, 620–626. CrossRef

Vander Heyden, F. (2014) Germination experiments with the southern African tree species *Pterocarpus angolensis*: in-vivo and in-vitro. MSc Thesis, University of Ghent, Gent.

Vermeulen, W.J. (1990) *A monograph on Pterocarpus angolensis*. Department of Environment Affairs, Water Affairs, and Forestry, Pretoria.

Von Breitenbach, F. (1973) *Pterocarpus angolensis.* A monograph. Trees in South Africa. *Journal of the Tree Society of South Africa*, **XXV**.

von Malitz, G.P. & Rathogwa, H.R. (1999) Dynamics of *Pterocarpus angolensis* (kiaat) in South Africa. Natural Forests and

Savanna Woodlands Symposium II, Knysna, South Africa.

Vyamana, V.G., Chamshama, S.A.O. & Mugasha, A.G. (2007) Effect of nursery practices on seedling survival and growth of selected miombo tree species, Morogoro, Tanzania. *Discovery and Innovation*, **19**, 122–138.

Weber, J.C., Montes, C.S., Kalinganire, A., Abasse, T. & Larwanou, M. (2015) Genetic variation and clines in growth and survival of *Prosopis africana* from Burkina Faso and Niger: comparing results and conclusions from a nursery test and a long-term field test in Niger. *Euphytica*, **205**, 809–821. CrossRef

Younan, R. (2015) *Germination experiment. Final report.* SASSCAL, Windhoek.

Development of a regional masters programme on dryland forestry

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Dryland forest resources have immense socioeconomic and ecological importance in southern Africa. These forests support the livelihood of growing populations and constitute an important buffer against climate change. However, there is currently a lack of capacity with respect to forestry professionals with sufficient expertise to implement adaptive resource management strategies in the face of climate change. To address this need, Stellenbosch University, in collaboration with other southern African forest scientists, developed a master's programme for dryland forestry (SASSCAL Task 079). It was decided to aim for a research-based MSc in Forestry (i.e., a programme based on the production of an MSc thesis) that would be supported by a number of elective short courses or modules. The elective coursework is designed to equip the student with additional research tools and the requisite knowledge to do independent research in the chosen field of study (http://www.sun.ac.za/english/faculty/agri/forestry/programmes/postgraduate). Dryland forestry touches on a wide variety of disciplines, and therefore, the elective short courses depend on the chosen specialisation of the candidate. The scope of the elective short courses was developed during workshops at Windhoek and Stellenbosch, and covers the following topics:

- Woodland ecology and silviculture
- Remote sensing and forest mensuration
- Tree improvement and nursery practice
- Biomass harvesting and transport logistics
- Wood processing and anatomy
- Dryland forest economics

The qualification is offered by Stellenbosch University and can accommodate both full-time and part-time students.

Figure 1: Allometric studies conducted by MSc graduate Martin Kambayi to determine carbon sequestration in the *Cryptocepalum* forest, Northwest Zambia. (Photo: M Kambayi)

Figure 2: PhD student Werner Mbongo inspects thinning of *Pterocarpus angolensis* at Okongo community forest, Namibia. (Photo: B du Toit)

Graduates and studies in process

The MSc forestry programme with dryland specialisation has attracted several students, working on diverse issues. The following topics have been studied since 2013 (student names and graduation dates in brackets).

1. Impact of fuelwood quality and quantity on rural households' energy use in Omusati region in the northwest of Namibia. (Hainduwa, F.N., 2013).
2. Assessment of trade-offs between timber and carbon values of *Pterocarpus angolensis* (Kiaat) in the Kavango region of Namibia: A comparison of current and potential values. (Moses, M., 2013).
3. Biomass modelling of selected drought-tolerant eucalypt species in South Africa. (Phiri, D., 2013).
4. Natural regeneration potential of *Pterocarpus angolensis* (Kiaat tree) in the dry forests of northern Namibia. (Kayofa, F., 2015).
5. Harvesting and postharvest handling practices of *Strychonos cocculoides* fruits in the Kavango West region of Namibia. (Elago, S.N., 2017).
6. Non-timber forest products in Zambia: Forest honey. (Nyawali, B., 2017)*.
7. Estimating carbon sequestered in an undisturbed *Cryptosepalum* forest in Mwinilunga District of North-Western Province, Zambia. (Kambayi, M., 2017)*.
8. The impact of fire on the natural regeneration of woody miombo species along a rainfall gradient. (Mwanza, P., 2018).
9. A study of the potential for *Eucalyptus* hybrids in farm forestry in the semi-arid winter rainfall region of South Africa. (Lambrechts, H.A., in process)*.
10. Post-harvesting carbon dynamics of cut stumps and root systems in industrial plantations. (Stephan, J.H.J., in process)*.
11. Estimation of below-ground carbon sequestration in eucalypt coppice stumps on a climate gradient. (Van Heerden, B., in process)*.
12. Effects of thinning intensity on the growth regeneration of *Burkea africana* and *Pterocarpus angolensis* in the Zambezian-Baikiaea woodlands. (Mbongo, W., PhD study in process)*.

** Students supported by Task 079 are indicated with an asterisk; the rest were/are funded externally, or by other SASSCAL Tasks).*

Impact of fire on the *Baikiaea* woodlands

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The tropical woodlands and savannas of southern Africa have amongst the highest fire frequencies in the world (Aldersley et al., 2011; Pausas & Ribeiro, 2013). Although fire has been a major driver of these ecosystems for millions of years (Bond & Zaloumis, 2016), most fires in the *Baikiaea* woodlands have an anthropogenic origin as the fire season is in the late dry season, when hardly any natural ignitions take place (Archibald et al., 2008; Gambiza et al., 2005; Stellmes et al., 2013). With northern Namibia and southern Angola projected to become warmer and drier, fire frequency is expected to increase (De Cauwer et al., 2016; Enright et al., 2015; Pausas & Ribeiro, 2013), as detected by some studies (Pricope & Binford, 2012; Schelstraete, 2016). The current fire regimes cause forest degradation, especially through the decrease of woody biomass and carbon sequestration (Chidumayo, 2013). Forest degradation is difficult to quantify as it requires comparison with an undegraded condition and often entails repeated measurements over time. Long-term studies in the *Baikiaea* woodlands have been very limited. One study of an annual burning experiment over 16 years in northern Namibia illustrated how fire negatively affected woody regeneration, especially of species such as *Baikiaea plurijuga* and *Commiphora* spp. (Geldenhuys, 1977). The SASSCAL task 038 assessed the impact of fire on the tree layer of the open *Baikiaea* woodlands at the border between Namibia and Angola, especially for trees with a minimum diameter at breast height (DBH) of 5 cm. A forest inventory was repeated after a period of one year to assess the impact of a single fire. Additionally, single forest inventory data were used to assess the impact of multiple fires on basal area and on tree damage.

Impact of a single fire on forest structure and tree damage

A comparison of forest structure and tree damage before and after a late dry season fire in northern Namibia was performed (Schelstraete, 2016). Forest structure was determined through stem density, basal area, and DBH derived from 33 forest inventory plots situated in Hamoye State Forest and 33 plots in Ncaute Community Forest. Tree damage was assessed through five subjective damage classes (0–4), from no damage to fatal damage (Fig. 1). Comparison of the forest inventory datasets, collected within a one-year interval, showed that there was no significant change in stem density, basal area, or DBH distribution of trees. The effect of the fire on forest composition was limited to a small increase in fire damage class for all tree diameters.

Figure 1: *Pterocarpus angolensis* with serious fire damage (fire damage class 3) at base of stem

Impact of multiple fires on basal area

The study of Schelstraete (2016) also assessed the fire frequency during the period 2001–2015 in the 66 inventory plots with MODIS (Stellmes et al., 2013) and Landsat images. Mean fire frequency was 2.2 fires in a plot over 15 years, or 15% for Hamoye and 17% for Ncaute. There was no significant relationship between fire frequency over a period of 15 years and basal area of three DBH classes in the plots. The basal area of *Burkea africana* and *Pterocarpus angolensis* did increase significantly with fire frequency in the more open community forest; this may be explained by the lower fire frequencies and higher harvesting intensities found closer to villages.

Impact of multiple fires on tree damage

Tree damage data were extracted from recent forest inventories in 217 sample plots in southern Angola and northern Namibia. Only 28% of the 3,779 stems recorded showed no damage, while 11% were fatally damaged or dead. Fire was the main cause of damage, with 45% of all stems showing fire damage. Fire damage increased slightly but significantly with DBH class (Fig. 2). Some woody species showed relatively more moderate to fatal fire damage (> 60% of stems), especially *Diplorhynchus condylocarpon*, *Dialium englerianum,* and *Strychnos pungens*. Species that appeared most resistant to fire, with less than 30% of the stems having moderate to fatal damage, were *Combretum psioides* and *Terminalia sericea*. The most fire-resistant timber species appeared to be *Pterocarpus angolensis* (Fig. 1), and the least resistant was *Guibourtia coleosperma,* with 28% and 53% of stems having moderate to fatal fire damage, respectively.

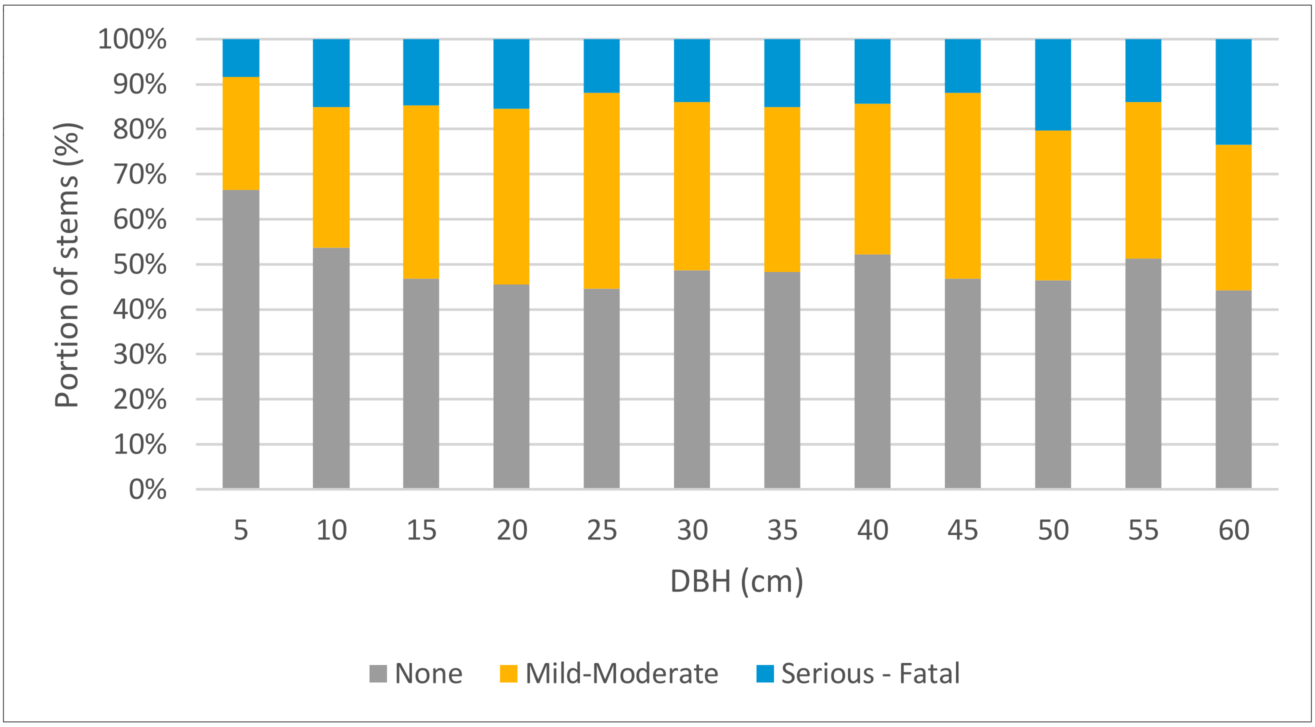

Figure 2: Fire damage per diameter at breast height (DBH) class for 3,648 stems collected in 217 inventory plots with a nested circular design up to 2,827 m^2 (data with DBH > 60 cm were excluded).

Conclusions

Although a single fire does not have an effect on tree layer composition, the accumulation of damage caused by recurring fires in the late dry season can result in early tree mortality and thus a decrease in wood biomass. Geldenhuys (1977) found that mid- to late dry season fires result in a significantly higher stem mortality compared to early burning or no burning. Studies with fire frequency measured over longer periods than 15 years should, however, be performed to learn more about the impact of fire on biomass and tree population dynamics in the *Baikiaea* woodlands. The effects of fire on tree damage and mortality vary with species, as is also the case for tree regeneration (Geldenhuys, 1977), thereby altering tree composition. A limitation of fire frequency and intensity is needed to protect certain socio-economically important species such as *Dialium englerianum* and *Guibourtia coleosperma*. Preventive management such as the reduction of the fuel load through grazing in the late growing season and early burning can reduce fire intensity and hence tree damage (Gambiza et al., 2008).

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References

Aldersley, A., Murray, S.J. & Cornell, S.E. (2011) Global and regional analysis of climate and human drivers of wildfire. *Science of the Total Environment*, **409**, 3472–3481.
Archibald, S., Roy, D.P., Wilgen, V., Brian, W. & Scholes, R.J. (2008) What limits fire? An examination of drivers of burnt area in Southern Africa. *Global Change Biology*, **15**, 613–630.
Bond, W. & Zaloumis, N.P. (2016) The deforestation story: testing for anthropogenic origins of Africa's flammable grassy biomes. *Philosophical Transactions of The Royal Society B Biological Sciences*, **371**, 20150170.
Chidumayo, E.N. (2013) Forest degradation and recovery in a miombo woodland landscape in Zambia: 22 years of observations on permanent sample plots. *Forest Ecology and Management*, **291**, 154–161.
De Cauwer, V., Geldenhuys, C.J., Aerts, R., Kabajani, M. & Muys, B. (2016) Patterns of forest composition and their long term environmental drivers in the tropical dry forest transition zone of southern Africa. *Forest Ecosystems*, **3**, 23.
Enright, N.J., Fontaine, J.B., Bowman, D.M., Bradstock, R.A. & Williams, R.J. (2015) Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. *Frontiers in Ecology and the Environment*, **13**, 265–272.
Gambiza, J., Campbell, B.M., Moe, S.R. & Frost, P.G. (2005) Fire behaviour in a semi-arid *Baikiaea plurijuga* savanna woodland on Kalahari sands in western Zimbabwe: research letter. *South African Journal of Science*, **101**, 239–244.
Gambiza, J., Campbell, B.M., Moe, S. & Mapaure, I. (2008) Season of grazing and stocking rate interactively affect fuel loads in Baikiaea plurijuga Harms woodland in northwestern Zimbabwe. *African Journal of Ecology*, **46**, 637–645.
Geldenhuys, C.J. (1977) The effect of different regimes of annual burning on two woodland communities in Kavango. *South African Forestry Journal*, 32–42.
Pausas, J.G. & Ribeiro, E. (2013) The global fire–productivity relationship. *Global Ecology and Biogeography*, **22**, 728–736.
Pricope, N.G. & Binford, M.W. (2012) A spatio-temporal analysis of fire recurrence and extent for semi-arid savanna ecosystems in southern Africa using moderate-resolution satellite imagery. *Journal of Environmental Management*, **100**, 72–85.
Schelstraete, M. (2016) Assessment of fire damage on the forest population near Hamoye, Kavango, Namibia.
Stellmes, M., Frantz, D., Finckh, M. & Revermann, R. (2013) Fire frequency, fire seasonality and fire intensity within the Okavango region derived from MODIS fire products. *Biodiversity and Ecology*, **5**, 351.

References [CrossRef]

Aldersley, A., Murray, S.J. & Cornell, S.E. (2011) Global and regional analysis of climate and human drivers of wildfire. *Science of the Total Environment*, **409**, 3472–3481. CrossRef

Archibald, S., Roy, D.P., Wilgen, V., Brian, W. & Scholes, R.J. (2008) What limits fire? An examination of drivers of burnt area in Southern Africa. *Global Change Biology*, **15**, 613–630. CrossRef

Bond, W. & Zaloumis, N.P. (2016) The deforestation story: testing for anthropogenic origins of Africa's flammable grassy biomes. *Philosophical Transactions of The Royal Society B Biological Sciences*, **371**, 20150170. CrossRef

Chidumayo, E.N. (2013) Forest degradation and recovery in a miombo woodland landscape in Zambia: 22 years of observations on permanent sample plots. *Forest Ecology and Management*, **291**, 154–161. CrossRef

De Cauwer, V., Geldenhuys, C.J., Aerts, R., Kabajani, M. & Muys, B. (2016) Patterns of forest composition and their long term environmental drivers in the tropical dry forest transition zone of southern Africa. *Forest Ecosystems*, **3**, 23. CrossRef

Enright, N.J., Fontaine, J.B., Bowman, D.M., Bradstock, R.A. & Williams, R.J. (2015) Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. *Frontiers in Ecology and the Environment*, **13**, 265–272. CrossRef

Gambiza, J., Campbell, B.M., Moe, S.R. & Frost, P.G. (2005) Fire behaviour in a semi-arid *Baikiaea plurijuga* savanna woodland on Kalahari sands in western Zimbabwe: research letter. *South African Journal of Science*, **101**, 239–244.

Gambiza, J., Campbell, B.M., Moe, S. & Mapaure, I. (2008) Season of grazing and stocking rate interactively affect fuel loads in Baikiaea plurijuga Harms woodland in northwestern Zimbabwe. *African Journal of Ecology*, **46**, 637–645. CrossRef

Geldenhuys, C.J. (1977) The effect of different regimes of annual burning on two woodland communities in Kavango. *South African Forestry Journal*, 32–42. CrossRef

Pausas, J.G. & Ribeiro, E. (2013) The global fire–productivity relationship. *Global Ecology and Biogeography*, **22**, 728–736. CrossRef

Pricope, N.G. & Binford, M.W. (2012) A spatio-temporal analysis of fire recurrence and extent for semi-arid savanna ecosystems in southern Africa using moderate-resolution satellite imagery. *Journal of Environmental Management*, **100**, 72–85. CrossRef

Schelstraete, M. (2016) Assessment of fire damage on the forest population near Hamoye, Kavango, Namibia.

Stellmes, M., Frantz, D., Finckh, M. & Revermann, R. (2013) Fire frequency, fire seasonality and fire intensity within the Okavango region derived from MODIS fire products. *Biodiversity and Ecology*, **5**, 351. CrossRef

Market analysis to assess timber products from dryland woodlots and farm forests in South Africa

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Abstract: The growing demand for renewable wood products and competition for land in South Africa will necessitate expansion of planted forests into moderately dry areas. Farm forestry and agroforestry options using species preselected for drought tolerance, water use efficiency, and pest/pathogen resistance may contribute to a sustainable timber supply. The feasibility of growing dryland farm forestry crops was tested as follows: current input costs and market prices of timber products were obtained in a market survey; growth data from existing dryland experiments were used together with four silvicultural regimes as forest growth model inputs; the yields per forest product class were modelled; and the land expectation values were calculated per regime over a range of site qualities. Projections indicate the best returns where pole markets are available, or where sawtimber plus small-scale poles are produced. With appropriate regime selection, attractive financial returns can be achieved on moderately low site qualities.

Resumo: A crescente procura de produtos de madeira renováveis e a concorrência por terras na África do Sul irão requerer a expansão das plantações florestais para zonas moderadamente secas. As opções de exploração florestal e agrofloresta que utilizam espécies pré-selecionadas para a tolerância à seca, eficiência do uso da água e resistência a pragas/patogénios, podem contribuir para um fornecimento sustentável de madeira. A viabilidade do crescimento de culturas de exploração florestal em terras áridas foi testada da seguinte forma: os custos dos insumos e os preços de mercado actuais foram obtidos num estudo de mercado; dados de crescimento de experiências já realizadas em terras áridas foram utilizados em conjunto com quatro regimes de silvicultura como insumos do modelo de crescimento florestal; os rendimentos por classe de produto florestal foram modelados; e os valores esperados da terra foram calculados por regime numa série de qualidades do local. As projecções indicam os melhores retornos onde os mercados madeireiros estão disponíveis, ou onde toras de madeira e postes de pequena escala são produzidos. Com a selecção do regime apropriado, retornos financeiros atractivos podem ser alcançados com qualidades de local moderamente baixas.

Introduction

South Africa relies heavily on its commercial plantation sector for timber and paper products. The forestry, timber, pulp, and paper (FTPP) sector currently plays a major role in South Africa with regards to contribution to the economy and employment: it contributed 10.2% to the agriculture GDP in South Africa during 2015 on 1% of the land base whilst supplying 158 000 direct employment opportunities (FSA, 2017). Commercial timber plantation forests cover approximately 1.224 million hectares of South Africa (FSA, 2017), with the main species planted comprising softwoods (pine species) and hardwoods (*Eucalyptus, Acacia,* and *Corymbia*). These plantations produced more than 18.7 million m^3 of commercial roundwood worth an estimated R 8.34 billion (delivered at mill cost) between 2011 and 2012 (DAFF, 2014). However, a growing population and an emphasis on renewable, carbon-friendly commodities compel the sector to increase its output. South Africa is approaching the limits of increasing productivity from a limited resource base, and the expansion of the plantation area in South Africa in areas where it is economically, environmentally and socially appropriate to do so is considered a priority (DAFF, 2013). Areas that are both available and suitable for commercial forestry in South Africa are limited, and much of this limitation is driven by a competition for water, a scarce resource in what is essentially a semi-arid country (Dyer, 2007). The major plantation forestry areas in South Africa are located in the summer rainfall region (on the eastern and southern seaboard of South Africa) and cover a wide range of soils and biophysical environments. Changes

Figure 1: Eucalyptus woodlots (a) the Pampoenvlei experimental site for dryland eucalyptus (age 22 years and mean annual precipitation during the trial period of the experiment = 453 mm); (b) short rotation experimental planting of eucalypts for pole and/or biomass production picturing *Eucalyptus grandis* x *camaldulensis* hybrids at age 7 years (mean annual precipitation = 800 mm). (Photos A. Clarin and G.F. Malherbe)

in temperature and rainfall regimes are likely to affect the extent and location of land climatically suitable for specific genotypes (Warburton & Schulze, 2008; DEA, 2013), thereby increasing the risk that optimal forestry areas may become marginal as a result of climate change.

The FTPP sector plays a significant role in rural areas in regions where few economic alternatives exist and can contribute significantly to rural economic development through forestry activities as well as through innovation in nontimber fibre products, fibre waste utilisation, and downstream processing activities. Given the challenges experienced by the forest industry and the role forestry plays in supporting rural economic development, there is a need to explore options for expanding the production of timber outside the traditional forestry areas (in moderately dry environments) as well as selecting and breeding tree species that are resilient to climate change. Selection and future breeding should be undertaken in light of climate projections since tree species and provenances differ in their ability to adapt to climate change. Selection criteria for species, hybrids, and clones should focus on traits related to drought tolerance, water efficiency, and resistance to pests and pathogens. This approach will support the need for a sustainable supply of products from woodlots and tree farms from dry climates to specific markets (du Toit & Malherbe, 2017).

The aim of the research was to investigate the potential markets for products primarily from species in the genus *Eucalyptus* that can be grown as farm forests or woodlots, specifically in dryland situations (Fig. 1). The reasons for the focus on this genus are that it has some of the highest water use efficiencies of indigenous and exotic taxa tested in South Africa to date (Gush & Dye, 2009) and that there is a well-established market of timber products from this genus (FSA, 2017). Furthermore, the ability to grow eucalypts in a farm forestry or agroforestry setting (i.e., in a mosaic pattern in appropriate landscape positions, alongside other land uses) usually does not compromise but often enhances food production. Examples are farm forests, outgrower schemes, woodlots, windbreaks, shelterbelts and silvo-pastoral systems, rehabilitation projects that may yield both timber products (Evans & Turnbull, 2004; Gardner, 2007; Wessels et al., 2016; du Toit et al., 2017a) and other services such as honey bee forage, pollination services (De Lange et al., 2013), increased yield in associated animal production systems (Broom et al., 2013; Alemu, 2016), and carbon sequestration systems and rehabilitation of salt-affected lands (du Toit & Malherbe, 2017; Harper et al., 2017). There is some concern over two commercially important pure eucalyptus species that have become invasive in South Africa (*E. grandis* and *E. camaldulensis*), although the genus *Eucalyptus* has generally produced relatively few invasive species worldwide (Rejmánek & Richardson, 2011). A number of species that were introduced to South Africa more than a century ago are not invasive (Forsyth et al., 2004), and there is no published evidence in the scientific literature to demonstrate invasiveness by eucalypt hybrid clones in South Africa. It follows that eucalypt tree planting (if an afforestation licence has been obtained) is a legitimate land use option that can also contribute to the rendering of ecosystem services such as pollination services, carbon sequestration and animal shelter on farms (De Lange et al., 2013; Harper et al., 2017). This article focuses on the economic feasibility of growing farm forestry crops in dryland areas by calculating the internal rate of return (IRR) and land expectation value (LEV) that can be achieved on combinations of site quality and silvicultural regime. This information can enable potential growers to understand the financial feasibility of any new investment in relation with the interest rate that can be earned from a similar investment at any financial institution. The IRR is defined as the discount

Table 1: Input costs used in FORSAT for IRR and LEV calculations (adjusted from Meyer, 2015).

Forestry activity	Year	Cost (R ha⁻¹) 1667 S ha⁻¹	Cost (R ha⁻¹) 1111 S ha⁻¹
Land value	0	8864.00	8864.00
Land preparation and pitting	0	1687.58	1124.72
Planting including watering	0	2088.43	1391.87
Fertilizing	0	1076.33	717.34
Blanking	0	379.82	253.14
Weeding	1	359.65	239.81
Weeding	2	359.65	239.81
Pruning	3	448.40	298.84
Fire protection (25% of commercial forestry)	annually	83.00	83.00
Administration (25% of commercial forestry)	annually	251.00	251.00
Harvesting	15	90.65 with bark, 125.04 debarked	90.65 with bark, 125.04 debarked

Table 2: Product dimensions and prices from a market survey (after du Toit et al., 2017b) used in FORSAT economic calculations.

Product	Min. diameter (cm)	Max. diameter (cm)	Min. length (m)	Max. length (m)	Price (R m⁻¹ delivered at roadside)
Sawlogs from high-wood-density species *	30	99	3.0	6.0	2000
Sawlogs	20	99	3.0	6.0	500
Small sawlogs	13	30	2.4	3.0	360
Pulp	6	99	1.8	3.0	177
Telephone and transmission poles	12	99	7.0	18	692
Building and fencing poles	7	15	1.2	7.0	350
Biomass	5	99	0.9	1.8	177

** The price is a weighted average where 30% of the sawn boards (by volume) are without sapwood and are suitable for outdoor decking grades while the remaining portion (70%) is sold as regular sawlog products.*

rate at which the net present value of a series of operational incomes minus costs over a tree crop rotation equals zero (Ham & Jacobson, 2012). The LEV is the present value (per hectare of plantation) of projected cash flows at rotation age (excluding the cost of land), as it is assumed that the rotation will repeat indefinitely (Ham & Jacobson, 2012). LEV is commonly used to evaluate financial feasibility of forestry projects (Ham & Jacobson, 2012) and is the preferred method of comparison between scenarios, especially when the rotation lengths between scenarios are different. The information described in this article is essentially a short summary of a more comprehensive report for SASSCAL Task 205 (du Toit et al., 2017b), and the reader is referred to this report for the finer details upon which results in this chapter are based. The detailed report includes an overview of the climatic, edaphic, regulatory and socio-economic realities in which dryland "farm timber products" could potentially be grown, the status quo of emerging grower schemes in South Africa, site-species matching and silvicultural regimes required for specific site-species combinations, and an economic analysis of growing trees for a variety of identified markets.

Methods

The Forestry Scenario Analysis Tool (FORSAT) has been designed by Kotze (2009) to estimate the stand growth rate and the production of specific roundwood products from plantations (as well as the economic gains) of the forest management scenarios being investigated. The tool essentially models stand growth based on site index and stand density information, taking into account the interaction between competition effects and site quality as measured in empirical experiments. Additional model out-

Table 3: Scenarios modelled for four regimes over five site indices indicating the potential product mix that could be grown (SI_5 = site index at base age 5 yrs; DBH = diameter at breast height).

Scenario number, regime and products	SI_5	S ha⁻¹ planted	Internal Rate of Return (IRR): Peak IRR (%)	IRR: Age at Peak IRR (yr)	Land Expectation Value (LEV): Peak LEV (R)	LEV: Age at Peak LEV (yr)	Dimensions and Volume at Peak LEV age (m³ ha⁻¹): DBH quadratic (cm)	HGT (m)	Stems ha⁻¹	Util Vol (m³)	Saw: decking	Saw: saw	Saw: small saw	Poles: tel	Poles: build& fencing	Pulp biomass	Thinning	Total
1. Pole production, planted 1667 S ha⁻¹ with no thinning	9	1667	3.71	25	2049	24	14.5	17.3	1066	102				53	49			102
	11	1667	6.43	21	17906	21	15.2	20.6	1133	142				89	53			142
	13	1667	9.34	15	37401	18	15.5	23.1	1203	178				112	66			178
	15	1667	12.35	12	61729	16	15.8	25.4	1251	215				138	77			215
	17	1667	15.58	10	90333	15	16.4	28.1	1275	263				173	90			263
	19	1667	19.01	9	124209	15	17.3	31.7	1275	335				232	103			335
2. Sawlog production, planted 1111 S ha⁻¹ with no thinning	9	1111	1.99	25	-314	25	16.8	18.5	801	109		19	46			44		109
	11	1111	4.01	25	4316	21	17.4	21.5	844	146		25	65			56		146
	13	1111	6.24	20	15437	20	18.6	25.2	855	200		45	93			62		200
	15	1111	8.57	16	28935	19	19.5	28.6	866	258		67	120			71		258
	17	1111	10.96	13	46291	19	20.7	32.7	866	339		117	144			78		339
	19	1111	13.4	11	66876	17	21.1	34.7	887	381		129	168			84		381
3. Sawlogs and poles, planted 1667 S ha⁻¹ with thinning *	9	1667	2.57	25	-2331	23	15.8	18.7	800	96		5	15		51		10	81
	11	1667	4.63	22	6881	22	17.1	22.5	800	143		13	62		68		18	161
	13	1667	6.95	18	20726	24	19.1	28.2	800	224	2	43	106		72		22	245
	15	1667	9.25	16	40267	25	20.7	33.3	800	322	8	89	139		85		29	350
	17	1667	11.94	15	66546	23	22.9	36.9	700	378	14	127	164		74		38	417
	19	1667	15.07	13	110831	25	26.5	43.2	600	514	52	222	181		59		39	553
4. Pulp and Biomass production, planted 1667 S ha⁻¹	9	1667	-1.52	25	-12433	25	14.7	17.7	1044	103						103		103
	11	1667	-0.22	25	-10218	25	16.2	22.5	1044	164						164		164
	13	1667	0.98	25	-7542	25	17.6	27.2	1044	238						238		238
	15	1667	2.1	22	-3534	20	17.2	28.6	1156	265						265		265
	17	1667	3.28	19	1087	17	17.2	30.1	1227	293						293		293
	19	1667	4.49	16	6454	16	17.9	32.8	1251	349						349		349

puts include the calculation of IRR and LEV, using methodology similar to that described by Ham & Jacobson (2012). The major model input values required are listed in Tables 1 and 2, and the following explanatory notes are given: Site quality is assessed by site index at base age 5 (SI_5), which is defined as the height (in metres) of the 20% largest diameter trees in a forest population at age 5 years. The site indices used in this comparison range from 9 to 19 m. The growth rates of best-performing species and hybrids in dryland eucalypt trials of southern Africa (Verryn et al., 1996; Gardner, 2001, 2007; Swain & Gardner, 2004; du Toit et al., 2017a) were comparable per aridity index class (du Toit et al., 2017b). We therefore chose to base site qualities in this report on the results from a series of trials in the Dryland Industrial and Rural Afforestation Programme (DIRAP). This series is situated on a transect from sub-humid to semi-arid regions in the Western Cape, with mean annual precipitation (MAP) ranging from 319 to 800 mm and aridity indices from 0.2 to 0.6 (du Toit et al., 2017a). [Aridity index is defined as mean annual precipitation / mean annual potential evapotranspiration]. These scenarios are thus presented for very low to medium site qualities that widely occur in southern Africa (compared to the generally higher site indices found in commercial plantation forestry) (Kotze et al., 2012). The industry averages of forestry activity costs for 2014 from Forestry Economic Services (Meyer, 2015) were used as a basis for calculating IRR and increased with the inflation rate to predict the costs for 2016 (Tab. 1). The 2016 product prices listed in Table 2 were derived from a South African industry market survey (du Toit et al., 2017b). Four scenarios were selected for the IRR calculations using FORSAT: The first scenario simulates areas close to pole treatment plants and no eucalypt sawlog markets. The primary products are telephone and transmission poles as well as building and fencing poles, with pulp or biomass as secondary products. The second scenario simulates conditions where a sawlog market is available and no pole market. The primary products are sawlogs and small sawlogs, with pulp

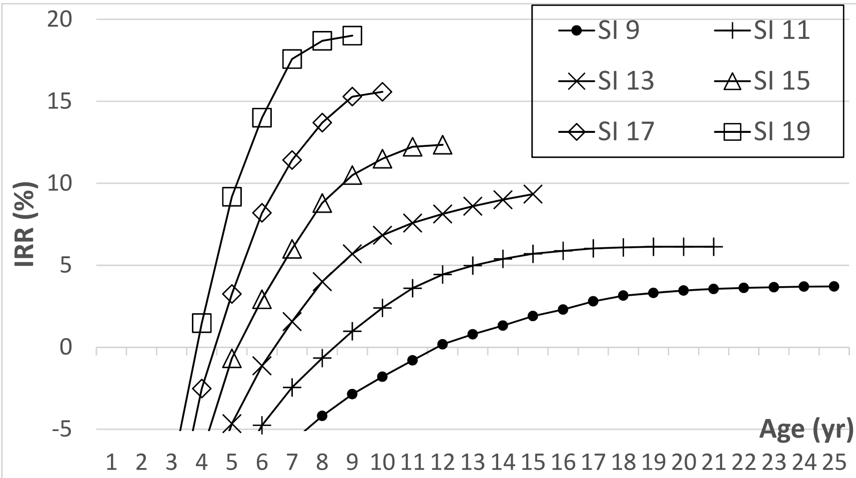

Figure 2: IRR for Scenario 1 (pole production) projected for five different site qualities.

or biomass as secondary products. The third scenario is a combination of poles from one mid-rotation thinning and the utilisation of poles and sawlogs at clear-fell age. A potential higher-value wood for decking is included in the third scenario to get an indication of the financial returns if a grower wants to extend the clear-fell age to 25 years. The fourth scenario simulates areas where no pole or sawlog markets exist and pulpwood or biomass, including firewood, is the only market. All management regimes consider a woodlot or plantation established at a density of 1 111 to 1 667 stems ha^{-1} (Tab.3). Thinnings (where applicable), were included in the model on a sliding scale as a function of site index: from thinning at 6 years (SI_5 = 19) to thinning at age 13 years (SI_5 = 9). The rotation length is strongly influenced by site quality and stocking: all models were run to 25 years of age, but the output graphs in Figures 2 to 5 were truncated at an age where the relative density exceeded a value of 8, indicating severe competition among trees (du Toit et al., 2017b). [The relative density is defined as stand basal area / ($Dq^{0.5}$), where basal area is measured in m^2 ha^{-1} and Dq = quadratic mean tree diameter (in cm)]. It will thus not be feasible to grow the stands in question on a longer rotation without thinning. The rotation length where LEV reached a peak is regarded as the optimum economic rotation length, and this rate (provided that it did not exceed the relative density criteria) was reported in Table 3 for each case study.

Results

The results of the IRR calculations are summarised in Figures 2–5, and the product volumes produced at given rotation ages plus their associated LEVs at the specified rotation lengths are shown in Table 3. The LEVs are strongly dependent on site quality (as modelled by SI_5) and the silvicultural regime (Tab. 3). Generally speaking, the two management regimes that included pole production as a main or secondary product were the most lucrative options across a wide range of site indices.

Scenario 1 (pole production only) yielded the best LEV across all site indices that had been tested. The IRR on the lowest site quality tested (SI_5 = 9) starts to realise a positive return when the rotation length exceeds 12 years, and it reaches a peak IRR of 4% at age 25. The corresponding IRR on the highest site quality tested (SI_5 = 19) starts to realise a positive return when the rotation length exceeds 3.8 years, and it reaches a peak IRR of 19% at age 9. (Fig. 2). The peak LEVs for the range of site indices tested span from R2 049 (SI_5 = 9; age 24) to R124 209 (SI_5= 19, age 15) (Tab. 3).

For Scenario 2 (sawlog production), the initial stand densities were reduced to 1 111 stems ha^{-1} in an attempt to allow trees to accelerate individual tree diameter growth, as it is not realistic to achieve sawlog dimensions in a short rotation on a low site index whilst maintaining high levels of stand density. With this regime, only a modest volume of sawlogs

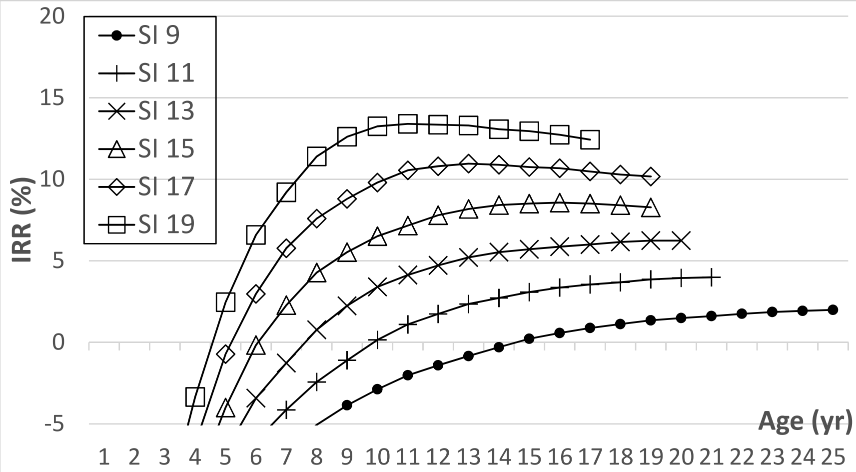

Figure 3: IRR for Scenario 2 (sawlog production), projected for five different site qualities.

(mostly in the small sawlog class) can be produced. The IRR on the lowest site quality tested (SI_5 = 9) starts to realise a positive return when the rotation length exceeds 14 years, and it reaches a peak IRR of 2.0% at age 25. The corresponding IRR on the highest site quality tested (SI_5 = 19) starts to realise a positive return when the rotation length exceeds 4.5 years, and it reaches a peak IRR of 13.4% at age 12. (Fig. 3). The peak LEVs for the range of site indices tested span from –R314 to R66 876 (Tab. 3), implying that a positive LEV can be achieved only with SI_5 = 10 or higher. As before, graph lines are truncated at the age when the relative density of the stand becomes risky (Fig. 3).

Scenario 3 (combination of poles from a mid-rotation thinning and sawlogs at clear-felling age) also turned out to be an economically attractive option for SI_5s greater than 10, provided that longer rotations are employed for the higher end of the reported site index range (Tab. 3). Note that no timber with decking dimensions is produced for the lower two site index classes (Tab. 3). In Scenario 3, the trajectories of the IRR plotted as a function of age are almost horizontal near the age of peak IRR, meaning that a near-optimum IRR can be obtained with a shorter or longer rotation. IRR on the lowest site quality tested (SI_5 = 9) starts to realise a positive return when the rotation length exceeds 12 years, and it reaches a peak IRR of 2.5% at age 23. The corresponding IRR on the highest site quality tested (SI_5 = 19) starts to realise a positive return when the rotation length exceeds 3.5 years, and it reaches a peak IRR of 15.1% at age 13. (Fig. 4). The peak LEVs for the range of site indices tested span from –R2 331 (SI_5 = 9; age 23) to R119 831 (SI_5= 19, age 25) (Tab. 3).

The LEVs for Scenario 4 (pulpwood, biomass, or firewood as the only available markets) were negative for site indices from 9 to 15, and on the two best site index classes, small positive numbers were obtained (Tab. 3).

Discussion

The results presented show that short-rotation pole crops (and to a lesser degree, sawlogs plus building/fencing poles from early thinnings) can be economically feasible production options for farm forests and woodlots in dry regions. The reader is reminded that the scenarios were run with realistic product costs but with lowered administration and fire protection input costs (Tab. 1), as the calculations were done to simulate a farm forestry/woodlot setting where the income of the landowner/forest manager and fire protection costs are supported by other activities besides forestry (coupled to the fact that a landscape with mixed agriculture and forestry land use usually has a lower fire risk profile). It must also be emphasized that FORSAT predicts the maximum utilizable volume of products based on input dimensions, negating the effect of losses due to poor stem form (i.e., a pole will be downgraded to pulp or biomass if it does not comply with the specifications for straightness, splitting and knots). For this reason, the real utilization might be lower than the predicted value, but the error factor will be the same for all products and the results are still useful in comparative studies as in this article. The main reasons for the superior economic performance of the pole crop simulated as Scenario 1 are (a) better volume utilization because the smaller thin-end specifications for poles are 5 cm for building and fencing, 7 cm for telephone and transmission poles (versus 13 cm for small sawlogs), and 20 cm for regular sawlogs; and (b) the fact that the past and current prices of poles are higher than those of sawlogs (du Toit et al., 2017b). On moderate-quality site indices, a relatively short rotation can be implemented whilst still reaching maximum LEVs, and this makes the whole operation also more risk-averse and suited to smaller-scale farmers.

Sawlog production with Scenario 2 did not fully utilize the site, and this is the main reason for its poor economic performance. It does not provide interim income from thinnings and it also poses a moderate biological risk, as the relative density values remain at a high level for an extended period near rotation end. The combination of all these factors makes this an undesirable option.

Scenario 3 (sawlogs plus building/fencing poles from early thinnings) was quite competitive with the pole-only crop of Scenario 1 (with the exception of the lower site qualities – Table 3). The denser initial planting followed by thinning for small pole classes allows for better site and stand volume utilization. It also ensures that trees with only moderately good stem form grow straighter than when planted on wide espacements (du Toit et al., 2017a). The relatively flat peaks of the IRR graphs (Fig. 4) mean that the forester has greater flexibility to shorten or lengthen the rotation as market prices dictate, without incurring significant losses. It is important to note that this scenario relies strongly on the premium paid for decking timber, and that prices will only apply to high-wood-density, low-splitting species such as *E. diversicolor*, *E. cladocalyx* and *E. gomphocephala* (Wessels et al., 2016) and are not applicable to *E. grandis* and

E. grandis hybrids. The sawmilling sector creates a large number of jobs per unit volume of timber produced, and is therefore very important in supporting rural livelihoods.

Timber production in South Africa is currently sufficient, with a net positive balance of trade (i.e., exports minus imports of wood products) (FSA, 2017), but the country's rapid population growth makes it unlikely that the balance will remain positive in the future. A strong case can thus be made for additional timber production. However, most of the currently undeveloped land in South Africa in the high-rainfall zones is not likely to become available for forestry because of competition for land. Furthermore, the aspirations of landless people have to be taken into account. Expansion into moderately dry areas is thus needed, and this places constraints on the species that can be grown, the regimes under which they can be grown, and the types of roundwood that can be produced. For example, timber regimes are not economically viable on low-productivity sites, but pole crops may offer a viable alternative. In addition, there are market limitations in some areas (e.g., no pulp markets in the Southern and Western Cape). Diversification into niche product markets such as pole crops and decking timber may be the catalyst that allows small-scale tree growers in sub-humid and semi-arid areas to develop economically viable opportunities for growing tree crops. If some of the additional environmental benefits from tree growing can generate income (e.g., pollination services, rehabilitation and maintenance of salt-affected lands, or carbon sequestration services), the economic scenarios become even more positive, as demonstrated in Western Australian case studies (Harper et al., 2017). The stream flow reduction if a catchment is *fully afforested,* on sites where MAP ranges from 650 to 800 mm, is estimated to be between 4 and 6% in the summer rainfall area, and between 2.5 and 3.5% in the winter rainfall area (Gush et al., 2002). Mosaic plantings of farm forests will have a significantly smaller impact than the numbers quoted because only a fraction of catchments will eventually be planted to trees, as currently regulated by the national afforestation licence system. In this way, additional water use by farm forests can be limited to a level that is balanced with other water users in each catchment. Economically viable dryland forests could stimulate the economy and help to eradicate poverty in rural areas whilst being based on a renewable, carbon-sequestering growing stock and subject to regulation of the total area planted in individual catchments, as is the status quo in South Africa.

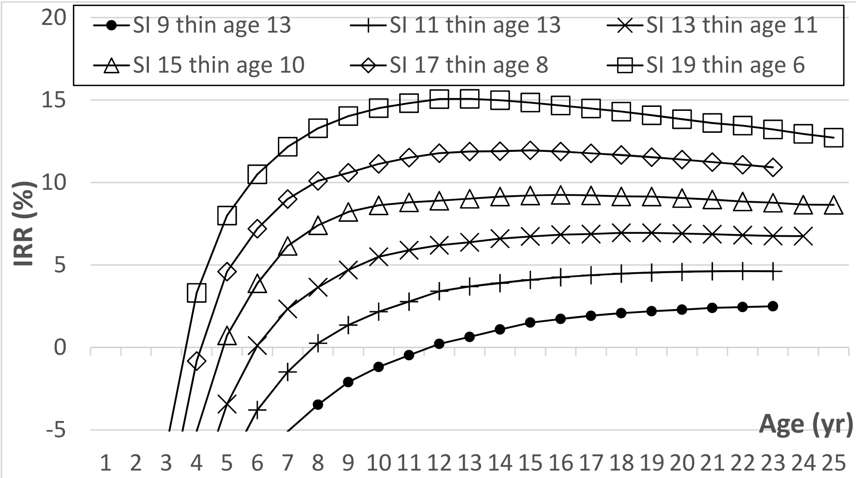

Figure 4: IRR for Scenario 3 (a combination of poles from a mid-rotation thinning and high-value sawlogs at clear-fell age), projected for five different site qualities.

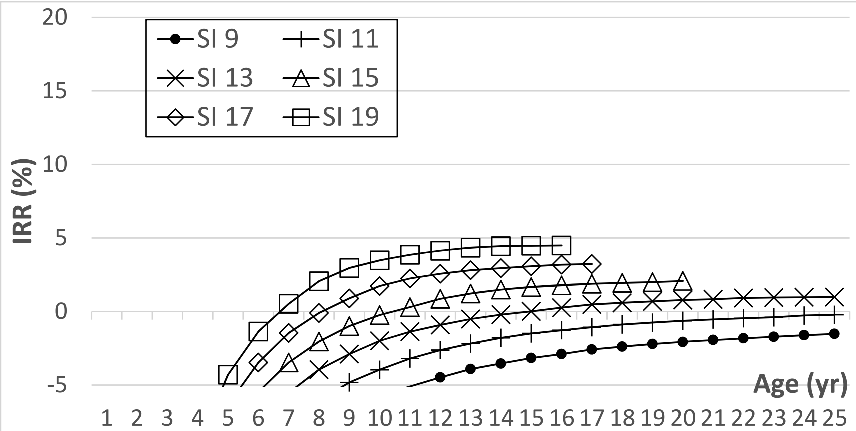

Figure 5: IRR for Scenario 4 (pulpwood and biomass production in the absence of poles or sawlogs markets), projected for five different site qualities.

Conclusions

The LEV projections for eucalypt farm forests and woodlots are strongly influenced by site quality and silvicultural regime, yielding the best returns where well-developed pole markets are available. The second best option is a combination of smaller classes of poles from a mid-rotation thinning and sawlogs at clear-felling age, using high-density species. The fact that the genus *Eucalyptus* has many species with rapid initial growth means that the maximum LEV is achieved in a time span that does not place it out of reach of small growers, even on moderately low-productivity sites in dry areas. The IRR results are a good indication that eucalypts can be grown profitably even on low-productivity sites (SI_5 around 10) and that financial returns in excess of 10% can be achieved on moderate site qualities (SI_5 of 15 to 20). At the same time, farm forestry projects could deliver several environmental benefits, some of which may also generate monetary income. Farm forestry in dryland areas should thus be viewed as an economically feasible land use that will also yield additional benefits such as job creation and various ecosystem services.

Forest resources

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References

Alemu, M.M. (2016) Ecological benefits of trees as windbreaks and shelterbelts. *International Journal of Ecosystem*, **6**, 10–13. doi:10.5923/j.ije.20160601.02

Broom, D.M., Galindo, F.A. & Murgueitio, E. (2013) Sustainable, efficient livestock production with high biodiversity and good welfare for animals. *Proceedings of the Royal Society B*, **280**, 2013–2025.

DAFF (2013) Strategic plan for the Department of Agriculture, Forestry and Fisheries. Department of Agriculture, Forestry and Fisheries, Pretoria, South Africa. http://www.daff.gov.za/doaDev/topMenu/DAFF%20Strategic%20Plan%202013.pdf Accessed 23 April 2015.

DAFF (2014) Report on commercial timber resources and primary roundwood processing in South Africa (2011/2012). Department of Agriculture, Forestry and Fisheries. Forestry Technical and Information Services, Forestry Economics Services CC, Pretoria, South Africa. http://www.forestry.co.za/uploads/File/industry_info/statistical_data/Nov%202014%20-%20Timber%20Statistics%20Report%202011%20-%202012.pdf. Accessed 22 April 2015

DEA (Department of Environmental Affairs) (2013) Long-Term Adaptation Scenarios Flagship Research Programme (LTAS) for South Africa. Climate change implications for the agriculture and forestry sectors in South Africa. Department of Environmental Affairs, Pretoria, South Africa.

De Lange, W.J., Veldtman, R. & Allsopp, M.H. (2013) Valuation of pollinator forage services provided by *Eucalyptus cladocalyx*. *Journal of Environmental Management*, **125**, 12–18.

du Toit, B. & Malherbe, G.F. (2017) A synopsis of silvicultural and management considerations for dryland forestry. *Southern Forests*, **79**, iii–v.

du Toit, B., Malherbe, G.F., Kunneke, A., Seifert, T., Wessels, C.B. (2017a) Survival and long-term growth results of Eucalypts on semi-arid sites in a Mediterranean climate, South Africa. *Southern Forests*, **79**, 235–249.

du Toit, B., Malherbe, G.F., Lambrechts, H., Naidoo, S. & Eatwell, K. (2017b) Market analysis to assess alternative forest products from dryland woodlots and farm forests in South Africa. CSIR Report no. CSIR/NRE/GC/IR/2017/0045/B. Council for Scientific and Industrial Research, Pretoria, South Africa.

Dyer, C. (2007) Forestry faces big issues to remain sustainable — a role for forestry research (Editorial). *Southern Hemisphere Forestry Journal*, **69**, iii–iv.

Evans, J. & Turnbull, J.W. (2004) Plantation forestry in the tropics. Oxford University Press, New York.

Forsyth, G.G., Richardson, D.M., Brown, P.J. & van Wilgen, B.W. (2004). A rapid assessment of the invasive status of *Eucalyptus* species in two South African provinces. *South African Journal of Science*, **100**, 75–77.

FSA (Forestry South Africa) (2017). The South African forestry and forest products industry 2015. Forestry South Africa.

http://www.forestry.co.za/uploads/File/industry_info/statistical_data/Jan%202017%20-%20South%20African%20Forestry%20and%20Forest%20Products%20Industry%202015.pptx.pdf. Accessed 5 July 2017.

Gardner, R.A.W. (2001) Alternative eucalypt species for Zululand: seven-year results of site-species interaction trials in the region. *Southern African Forestry Journal*, **19**, 79–88.

Gardner, R.A.W. (2007) Investigating the environmental adaptability of promising subtropical and cold-tolerant eucalypt species in the warm temperate climate zone of KwaZulu-Natal, South Africa. *Southern Hemisphere Forestry Journal*, **69**, 27–38.

Gush, M.B. & Dye, P.J. (2009) Water-use efficiency within a selection of indigenous and exotic tree species in South Africa as determined using sap flow and biomass measurements. Acta Horticulturae, **846**, 323–330.

Gush, M.B., Scott, D.F., Jewitt, G.P.W., Schulze, R.E., Hallowes, L.A. & Görgens, A.H.M. (2002). A new approach to modelling streamflow reductions resulting from commercial afforestation in South Africa. *Southern African Forestry Journal*, **196**, 27–36.

Ham, C. & Jacobson, M. (2012) Financial decision-making in forestry projects. *South African forestry handbook*, 5th edition (ed. by B.V. Bredenkamp & S. Upfold), pp. 491–500. Southern African Institute of Forestry, Pretoria, South Africa.

Harper, R.J., Sochacki, S.J. & McGrath, J.F. (2017) Developing reforestation options for dryland farmland in south-western Australia. *Southern Forests*, **79**, 185–196.

Kotze, H. (2009) Forestry Scenario Analysis Tool (FORSAT). User Manual Version 2.5. Internal document. Komatiland Forests (Pty) Ltd., Pretoria, South Africa.

Kotze, H., Kassier, H.W., Fletcher, Y. & Morley, T. (2012) Growth modelling and yield tables. *South African forestry handbook*, 5th edition (ed. by B.V. Bredenkamp & S. Upfold), pp. 175–210. Southern African Institute of Forestry, Pretoria, South Africa.

Meyer, W. (2015) *Detailed analysis and cost benchmark report. January 2014–December 2014.* Forestry Economics Services, Pietermaritzburg, South Africa.

Rejmánek, M. & Richardson, D.M. (2011) Eucalypts. *Encyclopedia of biological invasions* (ed. by D. Simberloff & M. Rejmánek), pp. 203–209. University of California Press, Berkeley.

Swain, T.L. & Gardner, R.A.W. (2004) Cold-tolerant eucalypts in South Africa – growth information for informed site-species matching in SA. *Southern African Forestry Journal*, 202, 83–84.

Verryn, S.D., Fairbanks, D., Pierce, B.T. & Dyer, C. (1996) Understanding the deployment of various eucalypt species and hybrids on a range of sites in southern Africa using fuzzy logic. *Tree improvement for sustainable tropical forestry* (ed. by M.J. Dieters, A.C. Matheson, D.G. Nikles, C.E. Harwood, & S.M. Walker), pp. 2:347-350. Proceedings of QFRI-IUFRO Conference, Caloundra, Queensland, Australia, 27 October–1 November 1996.Queensland forestry research institute, Queensland, Australia.

Warburton, M.L. & Schulze, R.E. (2008) Potential impacts of climate change on climatically suitable growth areas of *Pinus* and *Eucalyptus*: results from a sensitivity study in South Africa. *Southern Forests*, **70**, 27–36.

Wessels, C.B., Crafford, P.L., du Toit, B., Johansson, M., Lundqvist, S.-O., Säll, H. & Seifert, T. (2016) Variation in physical and lumber properties from three drought tolerant *Eucalyptus* species grown on the dry west coast of southern Africa. *European Journal of Wood and Wood Products*, **74**, 563–575.

References [CrossRef]

Alemu, M.M. (2016) Ecological benefits of trees as windbreaks and shelterbelts. *International Journal of Ecosystem*, **6**, 10–13. CrossRef

Broom, D.M., Galindo, F.A. & Murgueitio, E. (2013) Sustainable, efficient livestock production with high biodiversity and good welfare for animals. *Proceedings of the Royal Society B*, **280**, 2013–2025. CrossRef

DAFF (2013) Strategic plan for the Department of Agriculture, Forestry and Fisheries. Department of Agriculture, Forestry and Fisheries, Pretoria, South Africa. http://www.daff.gov.za/doaDev/topMenu/DAFF%20Strategic%20Plan%202013.pdf Accessed 23 April 2015.

DAFF (2014) Report on commercial timber resources and primary roundwood processing in South Africa (2011/2012). Department of Agriculture, Forestry and Fisheries. Forestry Technical and Information Services, Forestry Economics Services CC, Pretoria, South Africa. http://www.forestry.co.za/uploads/File/industry_info/statistical_data/Nov%202014%20-%20Timber%20Statistics%20Report%202011%20-%202012.pdf. Accessed 22 April 2015

DEA (Department of Environmental Affairs) (2013) Long-Term Adaptation Scenarios Flagship Research Programme (LTAS) for South Africa. Climate change implications for the agriculture and forestry sectors in South Africa. Department of Environmental Affairs, Pretoria, South Africa.

De Lange, W.J., Veldtman, R. & Allsopp, M.H. (2013) Valuation of pollinator forage services provided by *Eucalyptus cladocalyx*. *Journal of Environmental Management*, **125**, 12–18. CrossRef

du Toit, B. & Malherbe, G.F. (2017) A synopsis of silvicultural and management considerations for dryland forestry. *Southern Forests*, **79**, iii–v. CrossRef

du Toit, B., Malherbe, G.F., Kunneke, A., Seifert, T., Wessels, C.B. (2017a) Survival and long-term growth results of Eucalypts on semi-arid sites in a Mediterranean climate, South Africa. *Southern Forests*, **79**, 235–249. CrossRef

du Toit, B., Malherbe, G.F., Lambrechts, H., Naidoo, S. & Eatwell, K. (2017b) Market analysis to assess alternative forest products from dryland woodlots and farm forests in South Africa. CSIR Report no. CSIR/NRE/GC/IR/2017/0045/B. Council for Scientific and Industrial Research, Pretoria, South Africa.

Dyer, C. (2007) Forestry faces big issues to remain sustainable — a role for forestry research (Editorial). *Southern Hemisphere Forestry Journal*, **69**, iii–iv. CrossRef

Evans, J. & Turnbull, J.W. (2004) Plantation forestry in the tropics. Oxford University Press, New York.

Forsyth, G.G., Richardson, D.M., Brown, P.J. & van Wilgen, B.W. (2004). A rapid assessment of the invasive status of *Eucalyptus* species in two South African provinces. *South African Journal of Science*, **100**, 75–77.

FSA (Forestry South Africa) (2017). The South African forestry and forest products industry 2015. Forestry South Africa. http://www.forestry.co.za/uploads/File/industry_info/statistical_data/Jan%202017%20-%20South%20African%20Forestry%20and%20Forest%20Products%20Industry%202015.pptx.pdf. Accessed 5 July 2017.

Gardner, R.A.W. (2001) Alternative eucalypt species for Zululand: seven-year results of site-species interaction trials in the region. *Southern African Forestry Journal*, **19**, 79–88. CrossRef

Gardner, R.A.W. (2007) Investigating the environmental adaptability of promising subtropical and cold-tolerant eucalypt species in the warm temperate climate zone of KwaZulu-Natal, South Africa. *Southern Hemisphere Forestry Journal*, **69**, 27–38. CrossRef

Gush, M.B. & Dye, P.J. (2009) Water-use efficiency within a selection of indigenous and exotic tree species in South Africa as determined using sap flow and biomass measurements. Acta Horticulturae, **846**, 323–330. CrossRef

Gush, M.B., Scott, D.F., Jewitt, G.P.W., Schulze, R.E., Hallowes, L.A. & Görgens, A.H.M. (2002). A new approach to modelling streamflow reductions resulting from commercial afforestation in South Africa. *Southern African Forestry Journal*, **196**, 27–36. CrossRef

Ham, C. & Jacobson, M. (2012) Financial decision-making in forestry projects. *South African forestry handbook*, 5th edition (ed. by B.V. Bredenkamp & S. Upfold), pp. 491–500. Southern African Institute of Forestry, Pretoria, South Africa.

Harper, R.J., Sochacki, S.J. & McGrath, J.F. (2017) Developing reforestation options for dryland farmland in south-western Australia. *Southern Forests*, **79**, 185–196. CrossRef

Kotze, H. (2009) Forestry Scenario Analysis Tool (FORSAT). User Manual Version 2.5. Internal document. Komatiland Forests (Pty) Ltd., Pretoria, South Africa.

Kotze, H., Kassier, H.W., Fletcher, Y. & Morley, T. (2012) Growth modelling and yield tables. *South African forestry handbook*, 5th edition (ed. by B.V. Bredenkamp & S. Upfold), pp. 175–210. Southern African Institute of Forestry, Pretoria, South Africa.

Meyer, W. (2015) *Detailed analysis and cost benchmark report. January 2014–December 2014.* Forestry Economics Services, Pietermaritzburg, South Africa.

Rejmánek, M. & Richardson, D.M. (2011) Eucalypts. *Encyclopedia of biological invasions* (ed. by D. Simberloff & M. Rejmánek), pp. 203–209. University of California Press, Berkeley.

Swain, T.L. & Gardner, R.A.W. (2004) Cold-tolerant eucalypts in South Africa – growth information for informed site-species matching in SA. *Southern African Forestry Journal*, 202, 83–84. CrossRef

Verryn, S.D., Fairbanks, D., Pierce, B.T. & Dyer, C. (1996) Understanding the deployment of various eucalypt species and hybrids on a range of sites in southern Africa using fuzzy logic. *Tree improvement for sustainable tropical forestry* (ed. by M.J. Dieters, A.C. Matheson, D.G. Nikles, C.E. Harwood, & S.M. Walker), pp. 2:347-350. Proceedings of QFRI-IUFRO Conference, Caloundra, Queensland, Australia, 27 October–1 November 1996.Queensland forestry research institute, Queensland, Australia.

Warburton, M.L. & Schulze, R.E. (2008) Potential impacts of climate change on climatically suitable growth areas of *Pinus* and *Eucalyptus*: results from a sensitivity study in South Africa. *Southern Forests*, **70**, 27–36. CrossRef

Wessels, C.B., Crafford, P.L., du Toit, B., Johansson, M., Lundqvist, S.-O., Säll, H. & Seifert, T. (2016) Variation in physical and lumber properties from three drought tolerant *Eucalyptus* species grown on the dry west coast of southern Africa. *European Journal of Wood and Wood Products*, **74**, 563–575. CrossRef

Remote sensing-based environmental assessment and monitoring – generation of operational baseline and enhanced experimental products in southern Africa

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Abstract: The spatial extension of the countries covered by SASSCAL, the diversity of their landscapes, and the range of social and ecological processes, constitute a challenge to environmental research. The latter have sometimes needed to focus on small test sites for very specific questions, or else required data and methods that allowed large area assessments. In either situation it is important that the studies are founded on consistent and comparable data. Responding to this requirement, a range of products based on operational earth observation satellite systems has been developed in the frame of SASSCAL. Here, we introduce the most relevant primary and derived products at coarse (250–500 m MODIS) and medium (30 m Landsat) spatial resolution, describe their basic properties, and provide examples of application as an impetus for further research. At the same time, alternative sources of data and advances in sensor systems offer high potential in complementing information from operational products, or provide further insights into specific local questions. We thus briefly touch upon the potential of such systems, including active sensing and/or airborne technologies such as Synthetic Aperture Radar, Light Detection and Ranging, use of Unmanned Aerial Vehicles (UAV), and hyperspectral imaging, and introduce studies carried under SASSCAL using these systems.

Resumo: A extensão espacial dos países envolvidos com o SASSCAL, a diversidade das suas paisagens e a variedade dos processos sociais e ecológicos constituem um desafio para a pesquisa ambiental. O último aspecto necessitou, por vezes, de se focar em pequenos locais de teste para questões muito específicas, ou requerer dados e métodos que permitiram avaliações de grandes áreas. Porém, em qualquer das situações, é importante que os estudos se baseiem numa base de dados consistente e comparável. Em resposta a este requisito, e no âmbito do SASSCAL, foi desenvolvida uma gama de produtos com base nos sistemas de satélite operacionais de observação da Terra. Aqui, introduzimos os produtos primários e derivados mais relevantes em resolução espacial grosseira (250 – 500 m MODIS) e média (30 m Landsat), descrevemos as suas propriedades básicas e oferecemos exemplos de aplicação como um incentivo para posterior investigação. Simultaneamente, fontes alternativas de dados e avanços nos sistemas de sensores oferecem um alto potencial na complementação da informação de produtos operacionais, ou fornecem uma visão mais aprofundada sobre questões locais específicas. Assim, abordamos resumidamente o potencial de tais sistemas, incluindo tecnologias de detecção activa e/ou sistemas aéreos, tais como Radar de Abertura Sintética, tecnologia LIDAR (Light Detection and Ranging), Veículos Aéreos Não Tripulados (UAV) e sistemas de imagens hiperespectrais, e introduzimos estudos desenvolvidos no âmbito do SASSCAL que utilizaram estes sistemas.

Introduction

In the face of climate change and imminent transformation processes, the need to evaluate state indicators of social-ecological systems or monitor their development is more pressing than ever (Scholes et al., 2008; Verstraete et al., 2011). Aside from specifically tailored case studies, many questions can only be tackled at regional, national or even continental scales (e.g. reporting for the "Reducing Emissions from Deforestation and Forest Degradation" programme of the UNFCCC, Herold et al. (2011a)), thus requiring adequate datasets. Recent advances in sensor technology allow the derivation of more sophisticated environmental indicators than ever before. Whilst such approaches have been possible in recent years, they have often been limited to specific locations due to data costs or the need to employ experimental sensors.

On the other hand, and despite their limitations in terms of spectral, geometric and radiometric properties, the existence of freely accessible long-term remote sensing archives, such as those of NOAA-AVHRR, Landsat or MODIS, allows the tracking of environmental processes back to the early 1970s and across large areas. Recently Hansen et al. (2013) have provided a global estimation of deforestation between 2000 and 2013 based on Landsat imagery, and DeFries et al. (2007) have suggested a multi-scale framework for estimating greenhouse gas emissions from deforestation based on different sensor systems. In many cases, global, ready-to-use earth observation products are not adequate for specific research tasks such as time series or spectral analyses, and particular requirements emerge in terms of quantitative consistency standards and data pre-processing. For instance, applying advanced quantitative interpretation or classification techniques to sequences of optical data (e.g. Landsat or Sentinel-2) often requires these to be quantitatively consistent, necessitating correction of atmospheric effects, variations in sun position, influences of topography, etc. In the context of data with high temporal resolution (e.g. 16- or 8-day composite MODIS data), often only base products (reflectance, vegetation indices) often exist, while more ecologically meaningful data representing seasonal dynamics within and across years need to be specifically derived. Given the amount of data that can potentially be used, procuring pre-processed datasets for subsequent analyses poses considerable demands in terms of data volumes and processing capabilities.

Many applied users are interested in earth observation data but have no mandate or capability to deal with extensive data pre-processing strategies. For this reason, operational data processing frameworks may facilitate the use of satellite data in many fields. One example is the framework for optical remote sensing processing (Framework for Operational Radiometric Correction for Environmental monitoring, FORCE) that has been implemented to prepare data products at different processing levels. These may be utilised in a variety of applications and in response to requirements of different levels of users, ranging from large-area classification of land-use and land-cover units, to the detailed analysis of deforestation or forest degradation in a regional context.

In many cases, such products might be complemented by additional information derived from other sources. First and foremost, active systems like Synthetic Aperture Radar (SAR) is of interest here, with various spaceborne platforms having been launched in recent years, including Terra-SAR and Sentinel-1. ESA's Sentinel-1 fleet is the first SAR system to operationally provide global data at high spatial resolution of 10 by 10 m at no cost to the user. Numerous studies have demonstrated the potential of using radar data as standalone or in combination with optical data (Joshi et al., 2016). For instance, Reiche et al. (2015) have demonstrated the potential of improving Landsat-based NDVI time series with ALOS-PALSAR data to compensate for cloudiness and improve time series analysis. Likewise, Stefanski et al. (2014) combined Landsat-TM and ERS2-SAR data to significantly increase mapping accuracies of land management regimes in western Ukraine.

Besides spaceborne sensors, airborne systems offer unique potential in enhancing operational products or supplying specific datasets for local applications, for instance to provide biophysical and structural information on vegetation communities at plot level. Airborne single pulse or full waveform Light Detection and Ranging (LiDAR) systems have gained increasing attention for ecological studies (Lefsky et al., 2002) and in recent years there has been a growing number of studies of savanna systems (Lucas et al., 2011). Armston et al. (2013) directly retrieved canopy gap fraction from waveform LiDAR, while Lucas et al. (2006) demonstrated the use of local-scale airborne LiDAR data to calibrate radar-based biomass models of forest systems for larger areas. Airborne hyperspectral data are another valuable source of information, recording optical reflectance information in often more than 100 spectral bands. While such data may serve to map floristic patterns (Oldeland et al., 2010), their integration with active systems is particularly promising. Naidoo et al. (2012), Cho et al. (2012) and Colgan et al. (2012) presented different approaches of combining hyperspectral and LiDAR data to classify savanna tree species. Finally, Unmanned Aerial Vehicles (UAV) provide additional flexibility in data acquisition, since they can be operated at short notice without the need to organise fully-fledged flight campaigns. At the same time an increasing array of sensor systems from multi-spectral to hyperspectral and LiDAR sensors have become available (Colomina & Molina, 2104), and even simple multi-spectral systems that include near-infrared imaging capabilities can be useful in discriminating woody species in savanna systems (Oldeland et al., 2017).

Our paper describes the different operational remote sensing processing modules developed in the context of the SASSCAL initiative, introduces the derived products and refers to example applications. Further studies using active and experimental sensors carried out in the frame of the SASSCAL initiative are also described.

Methods

Coarse resolution products

The MODIS platforms Terra and Aqua have acquired earth observation data since the year 2000 and 2002 respectively, providing imagery of the entire globe within 1 to 2 days with a spatial resolution of 250 by 250 m to 1 by 1 km, depending on the spectral band. The spectral specifications of the MODIS sensors allow for the derivation of numerous products for monitoring land, oceans and the atmosphere. The land related products are mainly distributed by "The Land Processes Distributed Active Archive Center" (LP DAAC) within the NASA Earth Observing System Data and Information System (EOSDIS). Within SASSCAL, we were specifically interested in providing information on land cover characteristics as well as the fire regime covering the whole of southern Africa, comprising the countries Angola, Zambia, Namibia, Botswana, and South Africa.

Phenology metrics

Information on phenology is an important indicator for the characterisation of the status and dynamics of land use/cover (Andres et al., 1994). It can be reliably mapped from many earth observation systems, and is commonly associated with photosynthetic activity (or “greenness”) of vegetation. If such information is to be used for monitoring land cover dynamics, preferably long time periods need to be covered (Stellmes et al., 2013b). This information can be spatially provided by earth observation data with a high temporal repetition rate as acquired from sensors such as MODIS, SPOT-VEGETATION or NOAA-AVHRR.

To capture the land surface phenology (LSP) of the study region we used the 16-day Vegetation Indices (VI) Dataset at 250 m spatial resolution (Huete et al., 1999). It comprises different information layers, which are compiled from daily observations on a pixel basis from the best suitable information for the respective 16-day period. These layers include spectral vegetation indices (such as NDVI or EVI), reflectance values in different bands, and different auxiliary data on image acquisition conditions (e.g. viewing angles and observation quality). Importantly, for every pixel the exact date from which the data originated is recorded. The complete time series of the Terra and the Aqua MODIS sensors (MOD13Q1 and MYD13Q1 products, respectively) was incorporated for the period from 2000/2001 to 2012/2013. We used the Enhanced Vegetation Index (EVI) as a robust proxy for biomass development that reduces the impact of atmospheric influences and decouples the vegetation canopy signal from its background (i.e. soil and bedrock) signal based on reflectance in the blue, red and near-infrared bands. The day-of-composite information (i.e. the exact day from which a pixel in the composite originates) was used as the time axis and the Usefulness Index (Huete et al., 1999), an indication of the respective pixel’s assumed quality (considering aerosol quantity, atmospheric correction conditions, cloud cover, shadow and sun-target-viewing geometry) was used to weight the data points during the fitting procedure.

Figure 1: Three years of a MODIS Enhanced Vegetation Index (EVI) time series (thin line) and fitted smooth B-spline (thick line) (from Mader (2012); further information in the text).

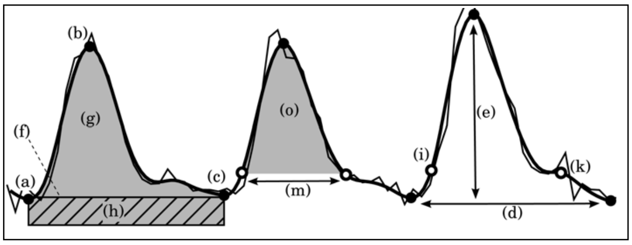


Table 1: Overview of parameters derived using the spline algorithm.

Index	Description	Ecological meaning
a	Day of year (DOY) and modelled value for early minimum of season (MOS)	Minimum greenness at beginning of the vegetation cycle and its day of occurrence
b	DOY and modelled value for peak of season (POS)	Maximum greenness within the vegetation cycle and its day of occurrence
c	DOY and modelled value for late minimum of season (MOS)	Minimum greenness at end of vegetation cycle and its day of occurrence
d	Duration (days) between successive minima	Length of vegetation cycle
e	Amplitude of Enhanced Vegetation Index (EVI) value as difference between peak and latent value (f)	Measure of the strength of the annual variability of greenness
f	Latent EVI value as average of the early and late minimum values	Measure related to the standing biomass
g	Integral between two successive minima	Measure related to the variable biomass
h	Latent integral	Measure related to the standing (invariant) biomass
g+h	Total integral defined as the sum of g and h	Measure related to the overall biomass within a vegetation cycle
i	Beginning (day of year) of greenness and modelled value for start of greenness	Metric related to the start of the vegetation period linked to a percent change in greenness and its day of occurrence
k	End (day of year) of greenness and modelled value for end of greenness	Metric related to the end of the vegetation period linked to a percent change in greenness and its day of occurrence
m	Duration of greenness defined as time span in days between i and k	Metric related to the length of the vegetation period as defined by the beginning and end of the vegetation period
o	Greenness integral defined by i and k	Metric related to the overall greenness/biomass generated within the vegetation period
	Rate of green-up defined as the slope of a line connecting the point of the onset of greenness and the annual peak value (not shown in Figure 1)	Metric related to the rate of greening up
	Rate of senescence, which is the (absolute) slope of the line connecting the annual peak and the point of end of greenness (not shown in Figure 1)	Metric related to the rate of senescence

MODIS LSP metrics were obtained by applying the Spline analysis of Time Series (SpliTS) algorithm (Mader, 2012). SpliTS is a C++ computer code for fitting spline models to remotely-sensed time series and to derive land surface phenology. It is a data-driven method that can handle non-equidistant time series considering the actual acquisition date. A set of 20 metrics is derived for each pixel, including date-specific parameters, and integral information about the growing seasons, amplitudes, etc., as illustrated in Figure 1 and summarised in Table 1.

Fire-related products

Changing boundary conditions, for example decreasing rainfall and/or land-use change related to population growth, may have major implications for the fire regime and in consequence for ecosystem functioning. Therefore, it is crucial to understand and describe all components of the prevailing fire regime. The key parameters that describe a fire regime are fire type, frequency, seasonality, intensity (largely determined by fuel load), spread and heat yield (Graz, 2003; Keeley, 2009).

We characterised the fire regime based on an extensive multi-scale compilation of the MODIS products “Active Fire” (AF) and “Burned Area” (BA) covering the period 2000 to 2015 and providing data with a spatial resolution of 1 km and 500 m, respectively. Based on the methodology proposed by Stellmes et al. (2013e), the integrated analysis of these mutually exclusive datasets allowed for a comprehensive spatio-temporal characterisation of important descriptors of the large-scale fire regime such as the fire frequency, seasonality and intensity, among others.

Moreover, we developed a novel object-based methodology that extracts valuable information about fire dynamics from BA data for every single fire detected and provides highly valuable information about fire dynamics that have not been spatially available up to now (Frantz et al., 2016e). Based on image segmentation of BA data and the analysis of movement trajectories between dates, detailed information for every single fire regarding timing and location of its ignition is recorded, as well as detailed directional multi-temporal spread information (i.e. the movement direction of the fire front and its speed). This information can in turn be integrated to derive large-scale information for the entire study area and to improve understanding of the overall fire regime.

Medium resolution products

Getting access to all recorded Landsat images, thanks to the opening of the archive (Woodcock et al., 2008), has provided unprecedented opportunities for long-term monitoring of a wide range of land surface indicators (Wulder et al., 2008; Danaher et al., 2010). In particular, it was possible to move from the analysis of a small set of images (Röder et al., 2008) to coverage of large areas (Griffiths et al., 2013a), and approaches utilising the full temporal depth of the Landsat archive (Kennedy et al., 2010). Yet, realising this potential poses challenges in terms of automated data pre-processing to ensure quantitative consistency of data.

Landsat archive pre-processing

We developed a pre-processing framework for Landsat imagery that incorporates the specific characteristics of the Thematic Mapper, Enhanced Thematic Mapper and Operative Land Imager sensors and adopts a tiling structure independent of the frames downloaded from Landsat’s World Reference System (WRS-2) (Frantz et al., 2016a). We download all L1T images with less than 70% cloud cover. This processing level includes radiometric calibration and ground control point-based orthorectification including a digital elevation model to account for relief displacement. Subsequently, a modified version of the FMask algorithm (Zhu & Woodcock, 2012) is utilised to detect clouds and cloud shadows for every image. It has been modified for enhanced performance in savanna ecosystems with their co-occurrence of surfaces of largely different colour and surface temperature (Frantz et al., 2015a). The core of the processing chain is based upon the formulation of the radiative transfer initially introduced by Tanré et al. (1990), which considers the impact of gases and aerosols on absorption, direct and diffuse scattering, the sun-sensor-surface configuration and environmental effects, and models these processes. To facilitate operational implementation, the algorithm is parameterised with consideration of aerosol optical thickness and water vapour transmission factors. The latter are derived from concurrent MODIS water vapour data (MOD05 and MYD05 products, MOD03 and MYD03 geolocation tables), or a fallback model based on seasonal date and location for Landsat images acquired prior to the MODIS era or where no appropriate MODIS dataset is available. Aerosol optical depth (AOD) is estimated over dark targets, making use of a precompiled dark object database. This holds pixels that have been identified as persistent dark features in a first iteration of all available images. Again, a fallback model based on seasonal date and location is employed where an image-based estimation is not possible. As an advancement over most large-area data production systems, a modified C-based topography-correction is included in the radiative transfer model, where the C factor is derived from a slope- and surface-class-specific linear regression between the cosine of the illumination angle and the spectral radiance from an inclined surface. As a further important element, a correction of bidirectional effects using global parameters supplied by (Roy et al., 2016) was implemented.

Finally, the resulting dataset is projected to tiles of 1000 x 1000 pixels (or 30 km x 30 km) using bilinear resampling and second-order polynomial warping to a Lambert azimuthal equal area projection centred at the KAZA Transfrontier Conservation Area. For technical details of any processing step, refer to Frantz et al. (Frantz et al., 2015c; Frantz et al., 2015a; Frantz et al., 2016a).

Phenology fusion

As has already been outlined in the Methods section of this chapter, satellite-derived land surface phenology (LSP) is an important source of information and may be utilised both to stratify further analyses and to serve as an important input component for land cover mapping, change detection and other processes (Stellmes et al., 2013b). The derivation of phenology metrics is most commonly based on images with a high temporal resolution, such as NOAA-AVHRR or MODIS, and using a range of methods, such as Fourier transform, wavelet transform or spline fitting (Jonsson & Eklundh, 2002). As a result, phenological metrics may be derived representing the long-term average situation or at yearly intervals, the latter also supporting time series analysis of phenological indicators (Stellmes et al., 2013b). Although many applications would benefit from the existence of phenology at higher resolutions (e.g. 30 m x 30 m corresponding to Landsat pixel size) their derivation is often complicated by limitations in data availability, which is particularly relevant in regions with distinct dry/wet season periods, such as those in many south-African countries. This shortcoming could be overcome by implementing image fusion algorithms such as StarFM (Gao et al., 2006) to simulate images with high spatial and temporal resolution, and use these to derive phenology metrics. However, this entails a massive overhead in terms of processing efforts and capacities required and may still not be feasible due to lack of sufficient image density (in particular during the wet season) and high landscape heterogeneity, which has been shown to reduce fusion quality. To overcome this, we have developed a method (*ImproPhe*) to predict selected phenology parameters at medium (Landsat) resolution (MR) directly from coarse resolution (CR) phenology (outlined in the Methods section). The method is based on the assumption that a few MR temporal observations are sufficient to separate image regions with similar phenology directly and to high precision, even if their temporal resolution would not allow the derivation of land surface phenology descriptors in a classic procedure (Frantz et al., 2016g). Accordingly, we relate the accurate CR LSP to the corresponding MR spatial features by exploiting their spatio-temporal patterns, which is similar to the StarFM approach (Gao et al., 2006). We define several proxies at both resolutions that define the final neighbouring pixel's weight. These proxies include the spectral distance, the heterogeneity of the MR pixels and the heterogeneity of CR pixels within the analysis window. To account for different units and ranges of input data and to increase the contrast between the best and worst weights, the retrieved neighbour weights are rescaled through a sigmoidal transfer function (Frantz et al., 2016g).

Phenology-adaptive image compositing

Considering the scale of many urgent environmental questions, and the need to cover large areas to meet reporting requirements such as those of the REDD+ programme (Herold et al., 2011b), specific challenges emerge concerning the appropriate input satellite products. In particular, cloud cover and processing capabilities may be obstacles to such large-area, wall-to-wall applications. With the availability of large data archives, mosaicking and compositing methods have emerged that can help to mitigate both constraints. While mosaicking commonly joins individual images, compositing is carried out at the pixel level. Numerous techniques have been developed, which are often based on the optimisation of band or index statistics (Flood et al., 2013) and aim at providing regularly spaced time series. Where adverse climatic settings and non-systematic acquisition plans prevent gap-free annual coverage, compositing approaches may consider observations from various years, which have first been combined with additional spectral criteria in a parametric weighting scheme by Griffiths et al. (2013b). One key aspect in such compositing schemes is the treatise of phenology, since the same type of vegetation community may be in different growing stages at one acquisition date due to different local climatic conditions. We therefore made use of the processed Landsat archive (outlined in the Methods section) and the phenology fusion approach (outlined in the Methods section) to develop a parametric weighting scheme that allows the generation of pixel-based, phenology-adaptive composites of Landsat surface reflectance data, i.e. the creation of "synthetic" images with pixels assembled from a large body of satellite images (Frantz et al., 2017). This technique employs a parametric weighting scheme with full consideration of annual land surface phenology (LSP) at the pixel scale to generate phenologically coherent composites. The technique may be applied to any gridded earth observation data archive and, in general, six metrics are used to evaluate the suitability of each pixel in the archive.

The target acquisition day (Day of Year, DOY) is based on phenology metrics and calculated for each pixel based on the target phenological state. Peak of Season (POS), End of Season (EOS), and Minimum of Season (MOS) are used to fit Gaussian or logistic S-curves, from which the scoring function for the respective target season is derived.

For each composite, a target year for the compositing is set. Since it is often not possible to find a phenologically suitable pixel in that particular year, a number of bracketing years are defined, and an additional factor accounts for the trade-off between phenologically suitable date and target year to yield the respective scoring value. The cloud distance score makes use of the cloud and cloud shadow mask resulting from the pre-processing scheme, and devaluates pixels that are potentially affected. In addition, the Haze Optimised Transformation (HOT, Zhu & Woodcock 2012) is additionally used as input to account for potential haze contamination of pixels that were not flagged as cloud or cloud shadow. A correlation score is introduced that evaluates the stability of a given pixel by relating it to its spectral behaviour over time, thus minimising the impact of noise in the data and efficiently preventing artefacts from being considered for the compositing. Finally, a view angle score is defined to favour near nadir observations to those at larger view angles. These scores are then calculated for every candidate pixel and at every position in the desired compositing region to identify the most suitable pixel.

In addition to the actual reflectance composite, a number of compositing metrics are computed that provide further information about the composite and can be used directly for different applications. These metrics include spectral average, standard deviation, kurtosis and skewness. Layers for each individual score and the overall score of the finally selected pixel are also generated (Frantz et al., 2017).

Results

Modis

Overall, 20 phenology metrics were derived for southern Africa on an annual basis (due to the growing season of the southern hemisphere starting in July) covering the period from 2000/2001 to 2012/2013.

Figure 2 depicts four phenological metrics that were derived for the SASSCAL countries. These are the means of: (i) the total integral, which can be related to the overall biomass; (ii) the latent integral associated with the standing biomass; (iii) the green integral, which is linked to the variable biomass within the vegetation period; and (iv) the day of year (DOY) of the start of greening. All metrics show that the study area is characterised by strong phenological gradients that can be related to the major functional vegetation types, to a large degree determined by climatological gradients. Whereas the subtropical Miombo belt in Angola and Zambia is characterised by a high total and latent integral, the Namib, which typifies the dry extreme of the study

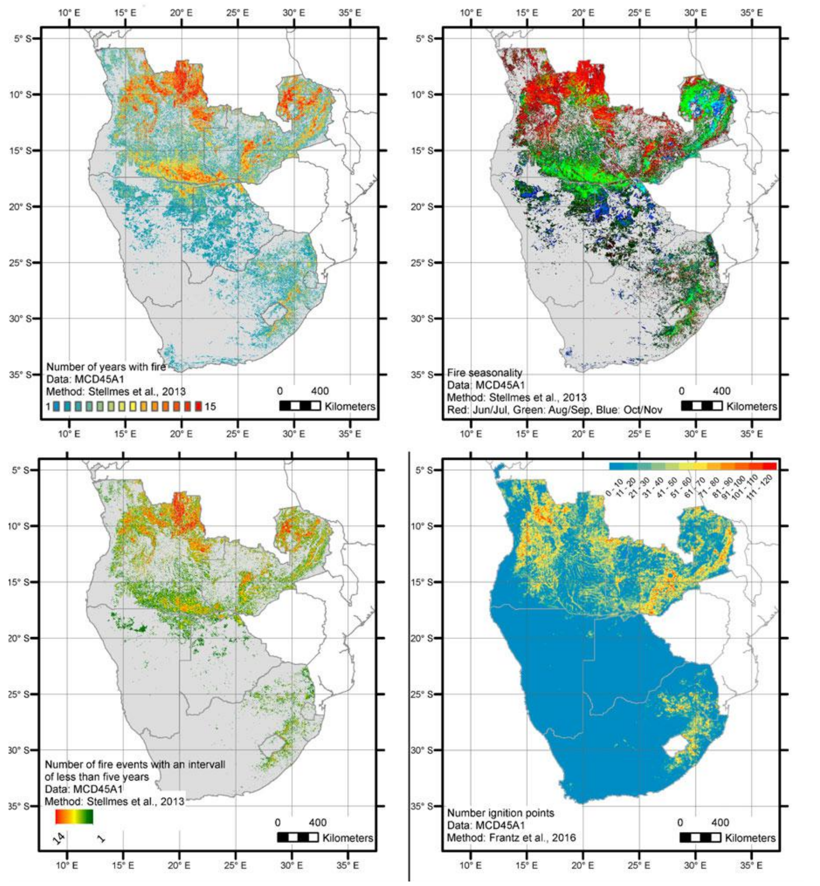
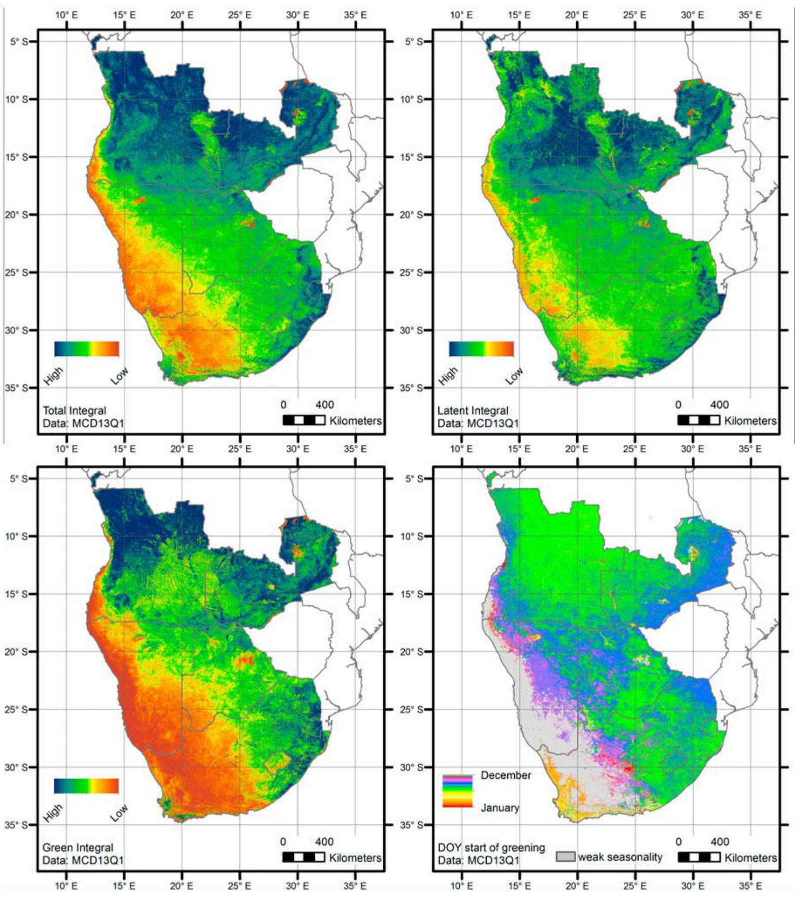


Figure 2: Remotely-sensed characterisation of the fire regimes of southern Africa. Number of years with fire (upper left), fire seasonality (upper right), number of fire events with an interval of less than five years (lower left) and number of ignition points within the period 2000 to 2015 (lower right).



area, is characterised by overall low vegetation cover. The phenology metrics are therefore capable of identifying the major functional vegetation types (Stellmes et al., 2013e) and might furthermore be utilised for large-area monitoring of land cover dynamics as well as for establishing relationships to climatic and anthropogenic drivers.

Fire related parameters

Based on the methodologies of Stellmes et al. (2013e) and Frantz et al. (2016e) a variety of fire regime related parameters were derived for the period covering 2000 to 2015. These parameters comprise established variables such as fire frequency, seasonality and intensity but also enhanced parameters such as the localisation of fire ignition points and fire spread rate. Figure 3 illustrates the capability of the used methodologies to provide important fire related information. The examples reveal the diversity of the fire regimes prevalent in the SASSCAL area, where fire frequency is high in grassland dominated ecosystems. These areas are therefore also characterised by high fire return intervals that are often too short to allow for the establishment of tree saplings. The fire seasonality is, in general terms, mainly characterised by a north—south gradient from early fires in June/July in northern Angola (red colour, Fig. 3) to later fires in the southern part (green and blue colours) that are often related to higher fire intensities.

Landsat

Landsat archive pre-processing

Covering the countries of Angola, Botswana, Namibia, Zambia, and Zimbabwe, we processed a total of 57,371 L1T images covering the period from 1984 to 2014, which corresponds to a surface area of 3.7 M km^2, 194 Landsat WRS-2 frames, 4524 tiles, 1,912,733 tiled datasets, and a total size of ~28 TB (Figure 4).

Figure 3: Mean total integral corresponding to total biomass (upper left), mean latent integral corresponding to standing biomass (upper right), mean green integral corresponding to variable biomass during the growing season (lower left) and day of year (DOY) of the start of greening for the observation period 2000/2001 to 2012/2013 (lower right).

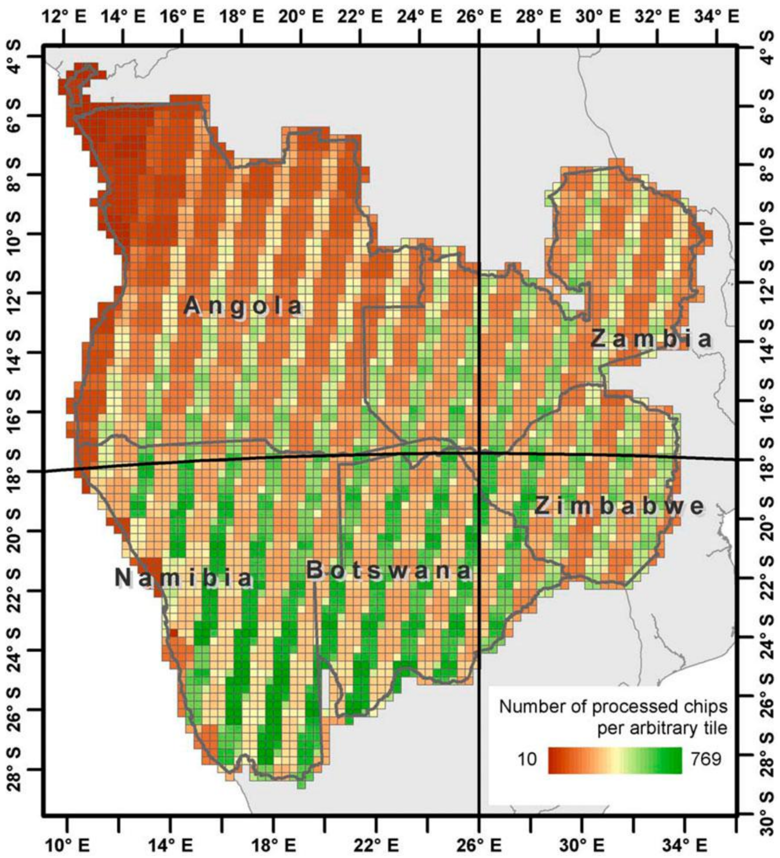


Figure 4: Number of processed Landsat images per tile. Redundant overlaps from the same path are excluded, whilst overlaps from neighbouring paths are visible as a striping pattern.

Since it is not feasible to carry out ground-based validation of reflectance values derived from large-area processing frameworks, we evaluated the spectral consistency of the results by making use of the along-path (i.e. consecutive rows) and across-path (i.e. neighbouring paths) overlap regions resulting from the image acquisition paths of Landsat data. We observed variations in the order of ±2.5% reflectance for 98.9% of all redundant image pairs. Furthermore, retrieved AOD estimates were compared with Aeronet stations located inside our project area with high coefficients of determination for all covered bands of the visible and near-infrared region. Uncertainty of water vapour absorption was assessed, and the robustness of the approach confirmed, through a sensitivity study over the Etosha pan, comparing values derived from the water vapour database with those derived from the MODIS products (Frantz et al. 2016a, b). The performance of the topography correction was evaluated by a relative analysis of NIR reflectance in different topographic aspect classes against a Minnaert-based correction and no correction, and our approach generally outperformed the other options (Frantz et al., 2015c; Frantz et al., 2016a).

All resulting images are stored in the gridded structure described before, where every tile contains all corrected reflectance images and the corresponding distances to the next cloud and cloud shadow. The structure is organised for easy data access, such that secondary indicators (e.g. vegetation indices) can be quickly calculated and stored as additional layers for further analysis.

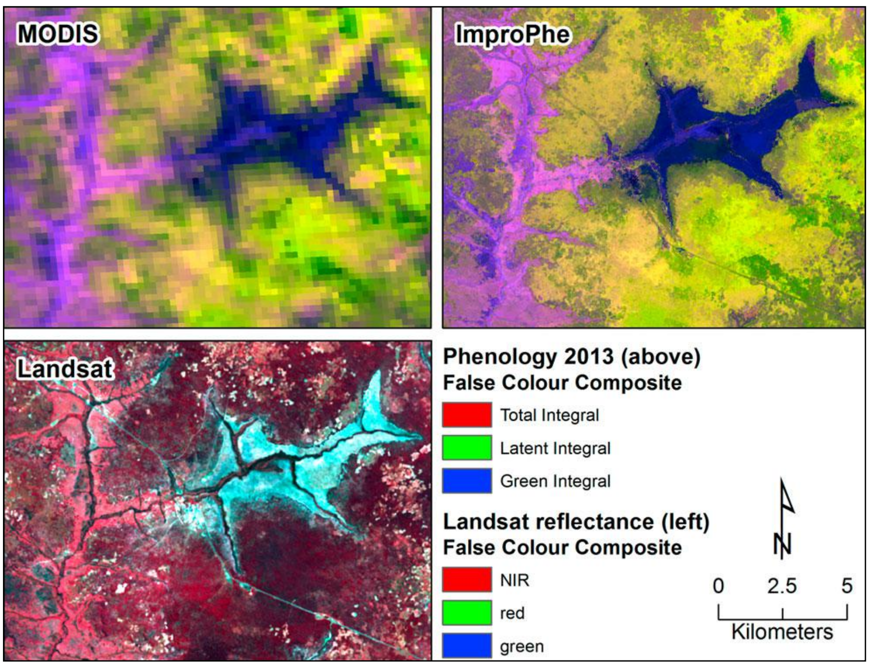


Figure 5: False colour composites of the Total Integral, Latent Integral and Green Integral in 2013. MODIS (above left), fusion result using the Improphe code (above right), and Landsat-8 image from May 2013 (below left).

Phenology fusion

We used MODIS-scale phenology as described before to parameterise the fusion algorithm. We evaluated the validity of our approach through a sensitivity study based on simulated data, which confirmed the performance of the different kernel-derived metrics (Frantz et al., 2016g). We then predicted the POS, EOS, MOS, and SOS (Start of Season) parameters for the 12-year period from 2001 to 2012 at Landsat spatial resolution for the entire study area and with a kernel size of 200 pixels. Figure 5 displays the prediction results as well as the input from the CR LSP.

Figure 5 shows the area around the city of Mumbué (Angola) characterised by the typical landscape elements in the study area. Whereas the valleys are dominated by grasslands, the summits are covered by dense Miombo forests, which are cleared for shifting cultivation purposes. The fused dataset substantially refines the spatial resolution of the LSP metrics and allows the better delineation of the land cover classes of the heterogeneous area compared to the MODIS LSP, while avoiding problems caused by data gaps when deriving LSP directly from Landsat time series. The grasslands are characterised by a high seasonal biomass (violet colour), the Miombo forests by high standing biomass (yellowish colour), whilst vegetation free areas show as dark blue colours. Arable land is quite diverse depending on whether the fields are in use or abandoned, but biomass amounts tend to be rather low compared to the natural vegetation cover. In general, object boundaries are well defined as shown in the agricultural areas, and even features that are barely discernible in the CR data, if at all, were reconstructed. Consequently, it is possible to predict at MR any phenological predictor existing at CR. The prediction quality is strongly dependent on the size of the analysis kernel, so the trade-off with processing time needs to be considered.

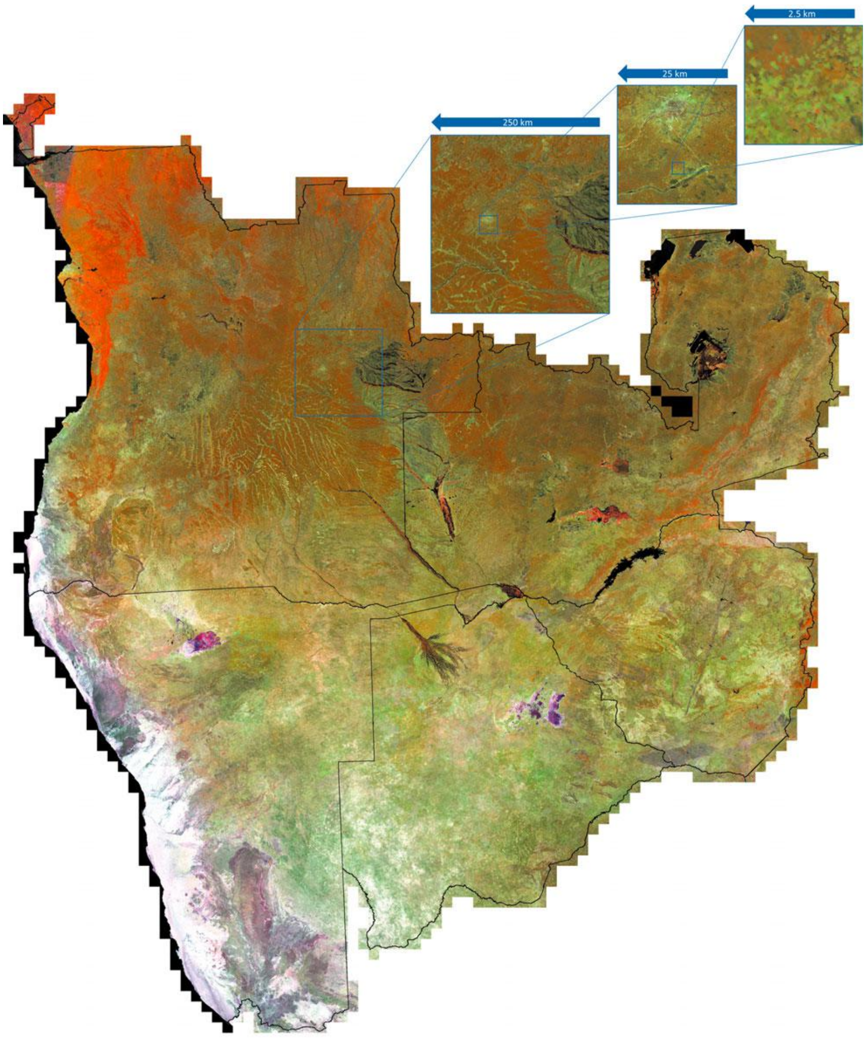


Figure 6: End-of-season composite of topography-corrected Landsat surface reflectance (RGB = Near Infrared – Short Wave Infrared – Red). Target year was 2008 ± 2 years.

Phenology-adaptive image compositing

We calculated different seasonal composites for varying target dates and years. Where no distinct yearly phenological cycles could be calculated (i.e. in the pre-MODIS era), a long-term average phenology was used instead. Figure 6 depicts a composite showing the countries of Angola, Botswana, Namibia, Zambia, and Zimbabwe.

The image shown here is a cloud-free, seamless Landsat representation of the full area with a composite size of 91000 x 82000 pixels and a total image size of approximately 80 GB. Roughly 208 M observations (i.e. pixels) were considered in the procedure; for ease of data handling, composites are commonly produced for smaller areas.

While cross-comparisons with composites derived from MODIS reflectance data underline the robustness of the approach, reduced data availability between the termination of Landsat-5 and the operational phase of Landsat-8, as well as enhanced cloudiness during the wet season, affect the quality of the composites produced, with SLC-off patterns related to Landsat-7 ETM+ being visible particularly in POS-composites. In general, the large difference between selecting individually tailored DOYs for each pixel, as opposed to defining a general DOY, was confirmed by evaluating the effect along altitudinal gradients. Consequently, selection of dynamic or static parameterisation of phenology in the compositing procedure requires careful consideration of the intended task. For instance, static parameterisation might be beneficial for crop type discrimination (Van Niel & McVicar, 2004), and tree type identification in areas with altitudinal gradients are expected to benefit from the phenological de-phasing associated with a dynamic parameterisation (Stoffels et al., 2015).

Discussion

This chapter introduced the main remote sensing based primary and secondary geospatial products that were developed in the context of SASSCAL. With their unique geometric, spectral and temporal characteristics, they allow a variety of questions related to environmental monitoring and modelling to be addressed, either by using the primary (spectral) data, or by utilising the derived products such as fire metrics, phenology descriptors or reflectance composites.

For instance, Stellmes et al. (2013a) have employed the derived phenology metrics at coarse scale to provide a map of major vegetation types for the Okavango Basin, Udelhoven et al. (2015) have analysed the influence of rainfall on vegetation trends using distributed lag models, and Revermann et al. (2016) have successfully linked phenology information to a vegetation database to model floral diversity. The medium resolution Landsat database has been employed to analyse conversion dynamics in a cross-border study in northern Namibia and southern Angola using iterative spectral mixture analysis and support vector classification (Röder et al., 2015), and in different analyses in central Angola using temporal segmentation of time series derived indicators (e.g. Normalized Burn Ratio, NBR; Disturbance Index, DI). The latter studies have identified patterns of conversion to smallholder agriculture (Schneibel et al., 2016) and analysed subtle changes within forests to identify processes of forest degradation (Schneibel et al., 2018), for instance caused by selective logging or charcoal production, and to identify underlying causes of deforestation (Parduhn & Frantz, 2018). De Blécourt et al. (2018) evaluated land-use change processes in smallholder-dominated systems in Zambia and Angola based on multi-temporal Landsat datasets. Since fires are a major component in any of these systems and cause major effects in spectral image properties, the fire products are, besides their relevance in ecological studies, important explanatory factors to understand spatial patterns derived from satellite imagery.

The combined use of long-term archives of coarse and medium resolution satellite data offers unique opportunities to address questions ranging from locally-adapted, specific case studies, to wall-to-wall approaches required for national reporting. At present, new sensors are becoming available that may be used to complement the archives introduced here, such as the suite of Sentinel systems. Our radiometric processing scheme has already been successfully tested with Sentinel-2A data in central European environments, and incorporation of these data will further enhance temporal revisit capabilities. Ideally, the processing can be realised in near-real-time, thus paving the way for the implementation of short-term early warning systems (Zhu & Woodcock, 2014).

Complementing the development of an operational processing framework and utilisation of its products, different complementary studies and experimental case studies are presented in this book. Making synergetic use of ALOS/PALSAR radar data with a range of LiDAR flight transects, Mathieu et al. (2018) introduce a woody cover dataset for South Africa and highlight the potential of woody cover monitoring for different test areas in south-western Africa. Strohbach (2018) and Knox et al. (2018) demonstrate the potential of UAV imagery to map ecosystem characteristics in Namibian woodland and rangeland systems based on vegetation indices and derived three-dimensional features, respectively.

In summary, remote sensing techniques have successfully contributed to addressing a plethora of environmental and societal questions, ranging from large area, wall-to-wall assessments to local and regional case studies, and make use of the full range of observation systems available today.

These observation and mapping capabilities can be expected to expand further with the range of upcoming systems. Since February 2016, Sentinel-3A provides complementary information to the MODIS system while Sentinel-1 radar imagery may be able to supply additional perspectives not yet covered by optical systems, such that a long-term perspective for large-area monitoring is ensured. As such, different levels of detail may be addressed, with novel very high resolution systems commonly operated by commercial companies (e.g. the dove suite of sensors launched by Planet Inc. or the Worldview satellites by Digitalglobe Inc.) or sensors mounted on unmanned aerial vehicles (UAV) being able to supply the crucial element to link ground-observations to the large-area perspective.

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References

Andres, L., Salas, W.A. & Skole, D. (1994) Fourier analysis of multi-temporal AVHRR data applied to a land cover classification. *Journal of Remote Sensing*, **115**, 1115-1121.

Armston, J., Disney, M., Lewis, P.E., Scarth, P., Phinn, S., Lucas, R., Buntin, P. & Goodwin, N. (2013) Direct retrieval of canopy gap probaility using airborne waveform lidar. *Remote Sensing of Environment*, **134**, 24-38.

Cho, M.A., Mathieu, R., Asner, G.P., Naidoo, L., van Aardt, J., Ramoelo, A., Debba, P., Wessels, K., Main, R., Smit, I.P.J. & Erasmus, B. (2012) Mapping tree species composition in South African savannas using an integrated airborne spectral and LiDAR system. *Remote Sensing of Environment*, **125**, 214-226.

Colgan, M.S., Baldeck, C.A., Féret, J.-B. & Asner, G.P. (2012) Mapping Savanna Tree Species at Ecosystem Scales Using Support Vector Machine Classification and BRDF Correction Airborne Hyperspectral and LiDAR Data. *Remote Sensing*, **4**, 3462-3480.

Colomina, I. & Molina, P. (2104) Unmanned aerial systems for photogrammetry and remote sensing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing*, **92**

Danaher, T., Scarth, P., Armston, J., Collett, L., Kitchen, J. & Gillingham, S. (2010) Remote Sensing of Tree-Grass Systems: The Eastern Australian Woodlands. *Ecosystem Function in Savannas: Measurement and Modeling at Landscape to Global Scales* (ed. by M.J. Hill and N.P. Hanan), pp. 175-194. CRC Press, Boca Raton, USA.

de Blécourt, M., Röder, A., Gröngröft, A., Baumann, S., Frantz, D. & Eschenbach, A. (2018) Deforestation for agricultural expansion in SW Zambia and NE Namibia and the impacts on soil fertility, and soil organic carbon and nutrient levels. This volume.

DeFries, R., Achard, F., Brown, S., Herold, M., Murdiyarso, D., Schlamadinger, B. & de Souza, C. (2007) Earth observations for estimating greenhouse gas emissions from deforestation in developing countries. *Environmental Science & Policy*, **10**, 385-394.

Flood, N., Danaher, T., Gill, T.K. & Gillingham, S.S. (2013) An Operational Scheme for Deriving Standardised Surface Reflectance from Landsat TM/ETM+ and SPOT HRG Imagery for Eastern Australia. *Remote Sensing*, **5**, 83-109.

Frantz, D., Röder, A., Udelhoven, T. & Schmidt, M. (2015a) Enhancing the Detectability of Clouds and Their Shadows in Multitemporal Dryland Landsat Imagery: Extending Fmask. *IEEE Geoscience and Remote Sensing Letters*, **12**, 1242-1246.

Frantz, D., Röder, A., Stellmes, M. & Hill, J. (2015c) On the Derivation of a Spatially Distributed Aerosol Climatology for its Incorporation in a Radiometric Landsat Preprocessing Framework. *Remote Sensing Letters*, **6**, 647-656.

Frantz, D., Röder, A., Stellmes, M. & Hill, J. (2016a) An Operational Radiometric Landsat Preprocessing Framework for Large-Area Time Series Applications. *IEEE Transactions on Geoscience and Remote Sensing*, **54**, 3928-3943.

Frantz, D., Stellmes, M., Röder, A. & Hill, J. (2016e) Fire spread from MODIS burned area data: obtaining fire dynamics information for every single fire. *International Journal of Wildland Fire*, -.

Frantz, D., Röder, A., Stellmes, M. & Hill, J. (2017) Phenology-adaptive pixel-based compositing using optical earth observation imagery. *Remote Sensing of Environment*, **190**, 331-347.

Frantz, D., Stellmes, M., Röder, A., Udelhoven, T., Mader, S. & Hill, J. (2016g) Improving the Spatial Resolution of Land Surface Phenology by Fusing Medium- and Coarse-Resolution Inputs. *IEEE Transactions on Geoscience and Remote Sensing*, **54**, 4153-4164.

Gao, F., Masek, J., Schwaller, M. & Hall, F. (2006) On the Blending of the Landsat and MODIS Surface Reflectance: Predicting Daily Landsat Surface Reflectance. *IEEE Transactions on Geoscience and Remote Sensing*, **44**, 2207-2218.

Graz, F.P. (2003) An HTML-based Concept Model of the Dry Savanna Woodland Ecosystem for Teaching and Learning. *Ecology & Society*, **7**, 9.

Griffiths, P., Müller, D., Kuemmerle, T. & Hostert, P. (2013a) Agricultural Land Change in the Carpathian Ecoregion after the Breakdown of Socialism and Expansion of the European Union. *Environmental Research Letters*, **8**

Griffiths, P., van der Linden, S., Kuemmerle, T. & Hostert, P. (2013b) A Pixel-Based Landsat Compositing Algorithm for Large Area Land Cover Mapping. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **6**, 2088-2101.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. & Townshend, J.R.G. (2013) High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, **342**, 850-853.

Herold, M., Roman-Cuesta, R.M., Mollicone, D., Hirata, Y., Van Laake, P., Asner, G.P., Souza, C., Skutsch, M., Avitabile, V. & MacDicken, K. (2011a) Options for monitoring and estimating historical carbon emissions from forest degradation in the context of REDD#. *Carbon Balance and Management*, **6**, 1-7.

Herold, M., Román-Cuesta, R.M., Mollicone, D., Hirata, Y., Van Laake, P., Asner, G.P., Souza, C., Skutsch, M., Avitabile, V. & MacDicken, K. (2011b) Options for Monitoring and Estimating Historical Carbon Emissions from Forest Degradation in the Context of REDD+. *Carbon Balance and Management*, **6**, 1-7.

Huete, A., Justice, C.O. & Van Leeuwen, W. (1999) MODIS vegetation index (MOD13). *Algorithm theoretical basis document*, **3**

Jonsson, P. & Eklundh, L. (2002) Seasonality Extraction by Function Fitting to Time-Series of Satellite Sensor Data. *IEEE Transactions on Geoscience and Remote Sensing*, **40**, 1824-1832.

Joshi, N., Baumann, M., Ehammer, A., Fensholt, R., Grogan, K., Hostert, P., Jepsen, M.R., Kuemmerle, T., Meyfroidt, P., Mitchard, E.T.A., Reiche, J., Ryan, C.M. & Waske, B. (2016) A Review of the Application of Optical and Radar Remote Sensing Data Fusion to Land Use Mapping and Monitoring. *Remote Sensing*, **8**, 1-23.

Keeley, J.E. (2009) Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire*, **18**, 116-126.

Kennedy, R.E., Yang, Z. & Cohen, W.B. (2010) Detecting Trends in Forest Disturbance and Recovery using Yearly Landsat Time Series: 1. LandTrendr — Temporal Segmentation Algorithms. *Remote Sensing of Environment*, **114**, 2897-2910.

Lefsky, M.A., Cohen, W.B., Parker, G., G. & Harding, D.J. (2002) Lidar Remote Sensing for Ecosystem Studies. *BioScience*, **52**, 19-30.

Lucas, R., Cronin, N., Lee, A., Moghaddam, M., Witte, C. & Tickle, P. (2006) Empirical relationships between AIRSAR backscatter and LiDAR-derived forest biomass, Queensland, Australia. *Remote Sensing of Environment*, **100**, 407-425.

Lucas, R., Lee, A., Armston, J., Carreiras, J.M.B., Viergever, K.M., Bunting, P., Clewley, D., Moghaddam, M., Siqueira, P. & Woodhouse, I. (2011) Quantifying Carbon in Savannas: The Role of Active Sensors in Measurements of Tree Structure and Biomass. *Ecosystem Function in Savannas: Measurement and Modelling at Landscape to Global Scales* (ed. by M.J. Hill and N.P. Hanan), pp. 155-174. CRC Press, Boca Raton, London, New York.

Mader, S. (2012) *A Framework for the Phenological Analysis of Hypertemporal Remote Sensing Data Based on Polynomial Spline Models*. Ph.D. dissertation, Trier University, Trier, Germany.

Naidoo, L., Cho, M.A., Mathieu, R. & Asner, G.P. (2012) Classification of savanna tree species, in the Greater Kruger National Park region, by integrating hyperspectral and LiDAR data in a Random Forest data mining environment. *ISPRS Journal of Photogrammetry and Remote Sensing*, **69**, 167-179.

Oldeland, J., Große-Stoltenberg, A., Naftal, L. & Strohbach, B.J. (2017) The Potential of UAV Derived Image Features for Discriminating Savannah Tree Species. *The Roles of Remote Sensing in Nature Conservation. A Practical Guide and Case Studies.* (ed. by R. Diaz-Delgado, R. Lucas and C. Hurford), pp. 183-202. Springer, London, New York.

Oldeland, J., Dorigo, W., Lieckfeld, L., Lucieer, A. & Jürgens, N. (2010) Combining vegetation indices, constrained ordination and fuzzy classification for mapping semi-natural vegetation units from hyperspectral imager. *Remote Sensing of Environment*, **114**, 1155-1166.

Parduhn, D. & Frantz, D. (2018) "This is not Deforestation". Seeing deforestation in Zambia from afar and nearby. This volume.

Reiche, J., Verbesselt, J., Hoekman, D. & Herold, M. (2015) Fusing Landsat and SAR time series to detect deforestation in the tropics. *Remote Sensing of Environment*, **156**, 276-293.

Revermann, R., Finckh, M., Stellmes, M., Strohbach, B., Frantz, D. & Oldeland, J. (2016) Linking land surface phenology and vegetation-plot databases to model terrestrial plant alpha diversity of the Okavango Basin. *Remote Sensing*, **8**, 470.

Röder, A., Udelhoven, T., Hill, J., del Barrio, G. & Tsiourlis, G. (2008) Trend Analysis of Landsat-TM and -ETM+ Imagery to Monitor Grazing Impact in a Rangeland Ecosystem in Northern Greece. *Remote Sensing of Environment*, **112**, 2863-2875.

Röder, A., Pröpper, M., Stellmes, M., Schneibel, A. & Hill, J. (2015) Assessing urban growth and rural land use transformations in a cross-border situation in Northern Namibia and Southern Angola. *Land Use Policy*, **42**, 340-354.

Roy, D.P., Zhang, H.K., Ju, J., Gomez-Dans, J.L., Lewis, P.E., Schaaf, C.B., Sun, Q., Li, J., Huang, H. & Kovalskyy, V. (2016) A General Method to Normalize Landsat Reflectance Data to Nadir BRDF Adjusted Reflectance. *Remote Sensing of Environment*, **176**, 255-271.

Schneibel, A., Röder, A., Stellmes, M. & Frantz, D. (2018) Long-term lan use change analysis in south-central Angola. Assessing the trade-off between major ecosystem services with remote sensing data. This volume.

Schneibel, A., Stellmes, M., Röder, A., Finckh, M., Revermann, R., Frantz, D. & Hill, J. (2016) Evaluating the trade-off between food and timber resulting from the conversion of Miombo forests to agricultural land in Angola using multi-temporal Landsat data. *Science of the Total Environment*, **548**, 390-401.

Scholes, R.J., Mace, G.M., Turner, W., Geller, G.N., Jürgens, N., Larigauderie, A., Muchoney, D., Walther, B.A. & Mooney, H.A. (2008) Toward a Global Biodiversity Observing System. *Science*, **321**, 1044-1045.

Stefanski, J., Kuemmerle, T., Chaskovskyy, O., Griffiths, P., Havryluk, V., Knorn, J., Korol, N., Sieber, A. & Waske, B. (2014) Mapping Land Management Regimes in Western Ukraine Using Optical and SAR Data. *Remote Sensing*, **6**, 5279-5305.

Stellmes, M., Frantz, D., Finckh, M. & Revermann, R. (2013a) Okavango Basin - Earth Observation. *Environmental Assessments in the Okavango region* (ed. by J. Oldeland, C. Erb, M. Finckh and N. Jürgens), pp. 23-27.

Stellmes, M., Röder, A., Udelhoven, T. & Hill, J. (2013b) Mapping Syndromes of Land Change in Spain with Remote Sensing Time Series, Demographic and Climatic Data. *Land Use Policy*, **30**, 685-702.

Stellmes, M., Frantz, D., Finckh, M., Revermann, R., Röder, A. & Hill, J. (2013e) Fire frequency, fire seasonality and fire intensity within the Okavango region derived from MODIS fire products. *Biodiversity & Ecology*, **5**, 351-362.

Stoffels, J., Hill, J., Sachtleber, T., Mader, S., Buddenbaum, H., Stern, O., Langshausen, J., Dietz, J. & Ontrup, G. (2015) Satellite-Based Derivation of High-Resolution Forest Information Layers for Operational Forest Management. *Forests*, **6**, 1982-2013.

Tanré, D., Deroo, C., Duhaut, P., Herman, M., Morcrette, J.J., Perbos, J. & Deschamps, P.Y. (1990) Description of a Computer Code to Simulate the Satellite Signal in the Solar Spectrum: The 5S Code. *International Journal of Remote Sensing*, **11**, 659-668.

Udelhoven, T., Stellmes, M. & Röder, A. (2015) Assessing rainfall-EVI relationships in the Okavango catchment employing MODIS time series data and distributed lag models. *Remote Sensing Time Series. Revealing Land Surface Dynamics* (ed. by C. Kuenzer, S. Dech and S. Wagner), pp. 225-245. Springer, Berlin, Heidelberg.

Van Niel, T.G. & McVicar, T.R. (2004) Determining Temporal Windows for Crop Discrimination with Remote Sensing: A Case Study in South-Eastern Australia. *Computers and Electronics in Agriculture*, **45**, 91-108.

Verstraete, M.M., Hutchinson, C.F., Grainger, A., Stafford Smith, M., Scholes, R.J., Reynolds, J.F., Barbosa, P., Léon, A. & Mbow, C. (2011) Towards a global drylands observing system: Observational requirements and institutional solutions. *Land Degradation & Development*, **22**, 198-213.

Woodcock, C.E., Allen, R., Anderson, M., Belward, A., Bindschadler, R., Cohen, W., Gao, F., Goward, S.N., Helder, D. & Helmer, E. (2008) Free Access to Landsat Imagery. *Science*, **320**, 1011a.

Wulder, M.A., White, J.C., Goward, S.N., Masek, J.G., Irons, J.R., Herold, M., Cohen, W.B., Loveland, T.R. & Woodcock, C.E. (2008) Landsat Continuity: Issues and Opportunities for Land Cover Monitoring. *Remote Sensing of Environment*, **112**, 955-969.

Zhu, Z. & Woodcock, C.E. (2012) Object-Based Cloud and Cloud Shadow Detection in Landsat Imagery. *Remote Sensing of Environment*, **118**, 83-94.

Zhu, Z. & Woodcock, C.E. (2014) Continuous Change Detection and Classification of Land Cover using all Available Landsat Data. Remote Sensing of Environment, 144, 152-171.

References [CrossRef]

Andres, L., Salas, W.A. & Skole, D. (1994) Fourier analysis of multi-temporal AVHRR data applied to a land cover classification. *Journal of Remote Sensing*, **115**, 1115-1121. CrossRef

Armston, J., Disney, M., Lewis, P.E., Scarth, P., Phinn, S., Lucas, R., Buntin, P. & Goodwin, N. (2013) Direct retrieval of canopy gap probability using airborne waveform lidar. *Remote Sensing of Environment*, **134**, 24-38. CrossRef

Cho, M.A., Mathieu, R., Asner, G.P., Naidoo, L., van Aardt, J., Ramoelo, A., Debba, P., Wessels, K., Main, R., Smit, I.P.J. & Erasmus, B. (2012) Mapping tree species composition in South African savannas using an integrated airborne spectral and LiDAR system. *Remote Sensing of Environment*, **125**, 214-226. CrossRef

Colgan, M.S., Baldeck, C.A., Féret, J.-B. & Asner, G.P. (2012) Mapping Savanna Tree Species at Ecosystem Scales Using Support Vector Machine Classification and BRDF Correction Airborne Hyperspectral and LiDAR Data. *Remote Sensing*, **4**, 3462-3480. CrossRef

Colomina, I. & Molina, P. (2104) Unmanned aerial systems for photogrammetry and remote sensing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing*, **92**

Danaher, T., Scarth, P., Armston, J., Collett, L., Kitchen, J. & Gillingham, S. (2010) Remote Sensing of Tree-Grass Systems: The Eastern Australian Woodlands. *Ecosystem Function in Savannas: Measurement and Modeling at Landscape to Global Scales* (ed. by M.J. Hill and N.P. Hanan), pp. 175-194. CRC Press, Boca Raton, USA.

de Blécourt, M., Röder, A., Gröngröft, A., Baumann, S., Frantz, D. & Eschenbach, A. (2018) Deforestation for agricultural expansion in SW Zambia and NE Namibia and the impacts on soil fertility, and soil organic carbon and nutrient levels. *This Volume*,

DeFries, R., Achard, F., Brown, S., Herold, M., Murdiyarso, D., Schlamadinger, B. & de Souza, C. (2007) Earth observations for estimating greenhouse gas emissions from deforestation in developing countries. *Environmental Science & Policy*, **10**, 385-394. CrossRef

Flood, N., Danaher, T., Gill, T.K. & Gillingham, S.S. (2013) An Operational Scheme for Deriving Standardised Surface Reflectance from Landsat TM/ETM+ and SPOT HRG Imagery for Eastern Australia. *Remote Sensing*, **5**, 83-109. CrossRef

Frantz, D., Röder, A., Udelhoven, T. & Schmidt, M. (2015a) Enhancing the Detectability of Clouds and Their Shadows in Multitemporal Dryland Landsat Imagery: Extending Fmask. *IEEE Geoscience and Remote Sensing Letters*, **12**, 1242-1246. CrossRef

Frantz, D., Röder, A., Stellmes, M. & Hill, J. (2015c) On the Derivation of a Spatially Distributed Aerosol Climatology for its Incorporation in a Radiometric Landsat Preprocessing Framework. *Remote Sensing Letters*, **6**, 647-656. CrossRef

Frantz, D., Röder, A., Stellmes, M. & Hill, J. (2016a) An Operational Radiometric Landsat Preprocessing Framework for Large-Area Time Series Applications. *IEEE Transactions on Geoscience and Remote Sensing*, **54**, 3928-3943. CrossRef

Frantz, D., Stellmes, M., Röder, A. & Hill, J. (2016e) Fire spread from MODIS burned area data: obtaining fire dynamics information for every single fire. *International Journal of Wildland Fire*. CrossRef

Frantz, D., Röder, A., Stellmes, M. & Hill, J. (2017) Phenology-adaptive pixel-based compositing using optical earth observation imagery. *Remote Sensing of Environment*, **190**, 331-347. CrossRef

Frantz, D., Stellmes, M., Röder, A., Udelhoven, T., Mader, S. & Hill, J. (2016g) Improving the Spatial Resolution of Land Surface Phenology by Fusing Medium- and Coarse-Resolution Inputs. *IEEE Transactions on Geoscience and Remote Sensing*, **54**, 4153-4164. CrossRef

Gao, F., Masek, J., Schwaller, M. & Hall, F. (2006) On the Blending of the Landsat and MODIS Surface Reflectance: Predicting Daily Landsat Surface Reflectance. *IEEE Transactions on Geoscience and Remote Sensing*, **44**, 2207-2218. CrossRef

Graz, F.P. (2003) An HTML-based Concept Model of the Dry Savanna Woodland Ecosystem for Teaching and Learning. *Ecology & Society*, **7**, 9. CrossRef

Griffiths, P., Müller, D., Kuemmerle, T. & Hostert, P. (2013a) Agricultural Land Change in the Carpathian Ecoregion after the Breakdown of Socialism and Expansion of the European Union. *Environmental Research Letters*, **8.** CrossRef

Griffiths, P., van der Linden, S., Kuemmerle, T. & Hostert, P. (2013b) A Pixel-Based Landsat Compositing Algorithm for Large Area Land Cover Mapping. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **6**, 2088-2101. CrossRef

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. & Townshend, J.R.G. (2013) High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, **342**, 850-853. CrossRef

Herold, M., Roman-Cuesta, R.M., Mollicone, D., Hirata, Y., Van Laake, P., Asner, G.P., Souza, C., Skutsch, M., Avitabile, V. & MacDicken, K. (2011a) Options for monitoring and estimating historical carbon emissions from forest degradation in the context of REDD#. *Carbon Balance and Management*, **6**, 1-7. CrossRef

Herold, M., Román-Cuesta, R.M., Mollicone, D., Hirata, Y., Van Laake, P., Asner, G.P., Souza, C., Skutsch, M., Avitabile, V. & MacDicken, K. (2011b) Options for Monitoring and Estimating Historical Carbon Emissions from Forest Degradation in the Context of REDD+. *Carbon Balance and Management*, **6**, 1-7. CrossRef

Huete, A., Justice, C.O. & Van Leeuwen, W. (1999) MODIS vegetation index (MOD13). *Algorithm theoretical basis document*, **3.**

Jonsson, P. & Eklundh, L. (2002) Seasonality Extraction by Function Fitting to Time-Series of Satellite Sensor Data. *IEEE Transactions on Geoscience and Remote Sensing*, **40**, 1824-1832. CrossRef

Joshi, N., Baumann, M., Ehammer, A., Fensholt, R., Grogan, K., Hostert, P., Jepsen, M.R., Kuemmerle, T., Meyfroidt, P., Mitchard, E.T.A., Reiche, J., Ryan, C.M. & Waske, B. (2016) A Review of the Application of Optical and Radar Remote Sensing Data Fusion to Land Use Mapping and Monitoring. *Remote Sensing*, **8**, 1-23. CrossRef

Keeley, J.E. (2009) Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire*, **18**, 116-126. CrossRef

Kennedy, R.E., Yang, Z. & Cohen, W.B. (2010) Detecting Trends in Forest Disturbance and Recovery using Yearly Landsat Time Series: 1. LandTrendr — Temporal Segmentation Algorithms. *Remote Sensing of Environment*, **114**, 2897-2910. CrossRef

Lefsky, M.A., Cohen, W.B., Parker, G., G. & Harding, D.J. (2002) Lidar Remote Sensing for Ecosystem Studies. *BioScience*, **52**, 19-30. CrossRef

Lucas, R., Cronin, N., Lee, A., Moghaddam, M., Witte, C. & Tickle, P. (2006) Empirical relationships between AIRSAR backscatter and LiDAR-derived forest biomass, Queensland, Australia. *Remote Sensing of Environment*, **100**, 407-425. CrossRef

Lucas, R., Lee, A., Armston, J., Carreiras, J.M.B., Viergever, K.M., Bunting, P., Clewley, D., Moghaddam, M., Siqueira, P. & Woodhouse, I. (2011) Quantifying Carbon in Savannas: The Role of Active Sensors in Measurements of Tree Structure and Biomass. *Ecosystem Function in Savannas: Measurement and Modelling at Landscape to Global Scales* (ed. by M.J. Hill and N.P. Hanan), pp. 155-174. CRC Press, Boca Raton, London, New York.

Mader, S. (2012) *A Framework for the Phenological Analysis of Hypertemporal Remote Sensing Data Based on Polynomial Spline Models*. Ph.D. dissertation, Trier University, Trier, Germany.

Naidoo, L., Cho, M.A., Mathieu, R. & Asner, G.P. (2012) Classification of savanna tree species, in the Greater Kruger National Park region, by integrating hyperspectral and LiDAR data in a Random Forest data mining environment. *ISPRS Journal of Photogrammetry and Remote Sensing*, **69**, 167-179. CrossRef

Oldeland, J., Große-Stoltenberg, A., Naftal, L. & Strohbach, B.J. (2017) The Potential of UAV Derived Image Features for Discriminating Savannah Tree Species. *The Roles of Remote Sensing in Nature Conservation. A Practical Guide and Case Studies.* (ed. by R. Diaz-Delgado, R. Lucas and C. Hurford), pp. 183-202. Springer, London, New York.

Oldeland, J., Dorigo, W., Lieckfeld, L., Lucieer, A. & Jürgens, N. (2010) Combining vegetation indices, constrained ordination and fuzzy classification for mapping semi-natural vegetation units from hyperspectral imager. *Remote Sensing of Environment*, **114**, 1155-1166. CrossRef

Parduhn, D. & Frantz, D. (2018) "This is not Deforestation". Seeing deforestation in Zambia from afar and nearby. *This Volume*,

Reiche, J., Verbesselt, J., Hoekman, D. & Herold, M. (2015) Fusing Landsat and SAR time series to detect deforestation in the tropics. *Remote Sensing of Environment*, **156**, 276-293. CrossRef

Revermann, R., Finckh, M., Stellmes, M., Strohbach, B., Frantz, D. & Oldeland, J. (2016) Linking land surface phenology and vegetation-plot databases to model terrestrial plant alpha diversity of the Okavango Basin. *Remote Sensing*, **8**, 470. CrossRef

Röder, A., Udelhoven, T., Hill, J., del Barrio, G. & Tsiourlis, G. (2008) Trend Analysis of Landsat-TM and -ETM+ Imagery to Monitor Grazing Impact in a Rangeland Ecosystem in Northern Greece. *Remote Sensing of Environment*, **112**, 2863-2875. CrossRef

Röder, A., Pröpper, M., Stellmes, M., Schneibel, A. & Hill, J. (2015) Assessing urban growth and rural land use transformations in a cross-border situation in Northern Namibia and Southern Angola. *Land Use Policy*, **42**, 340-354. CrossRef

Roy, D.P., Zhang, H.K., Ju, J., Gomez-Dans, J.L., Lewis, P.E., Schaaf, C.B., Sun, Q., Li, J., Huang, H. & Kovalskyy, V. (2016) A General Method to Normalize Landsat Reflectance Data to Nadir BRDF Adjusted Reflectance. *Remote Sensing of Environment*, **176**, 255-271. CrossRef

Schneibel, A., Röder, A., Stellmes, M. & Frantz, D. (2018) Long-term lan use change analysis in south-central Angola. Assessing the trade-off between major ecosystem services with remote sensing data. This Volume. CrossRef

Schneibel, A., Stellmes, M., Röder, A., Finckh, M., Revermann, R., Frantz, D. & Hill, J. (2016) Evaluating the trade-off between food and timber resulting from the conversion of Miombo forests to agricultural land in Angola using multi-temporal Landsat data. *Science of the Total Environment*, **548**, 390-401. CrossRef

Scholes, R.J., Mace, G.M., Turner, W., Geller, G.N., Jürgens, N., Larigauderie, A., Muchoney, D., Walther, B.A. & Mooney, H.A. (2008) Toward a Global Biodiversity Observing System. *Science*, **321**, 1044-1045. CrossRef

Stefanski, J., Kuemmerle, T., Chaskovskyy, O., Griffiths, P., Havryluk, V., Knorn, J., Korol, N., Sieber, A. & Waske, B. (2014) Mapping Land Management Regimes in Western Ukraine Using Optical and SAR Data. *Remote Sensing*, **6**, 5279-5305. CrossRef

Stellmes, M., Frantz, D., Finckh, M. & Revermann, R. (2013a) Okavango Basin - Earth Observation. *Environmental Assessments in the Okavango region* (ed. by J. Oldeland, C. Erb, M. Finckh and N. Jürgens), pp. 23-27. CrossRef

Stellmes, M., Röder, A., Udelhoven, T. & Hill, J. (2013b) Mapping Syndromes of Land Change in Spain with Remote Sensing Time Series, Demographic and Climatic Data. *Land Use Policy*, **30**, 685-702. CrossRef

Stellmes, M., Frantz, D., Finckh, M., Revermann, R., Röder, A. & Hill, J. (2013e) Fire frequency, fire seasonality and fire intensity within the Okavango region derived from MODIS fire products. *Biodiversity & Ecology*, **5**, 351-362. CrossRef

Stoffels, J., Hill, J., Sachtleber, T., Mader, S., Buddenbaum, H., Stern, O., Langshausen, J., Dietz, J. & Ontrup, G. (2015) Satellite-Based Derivation of High-Resolution Forest Information Layers for Operational Forest Management. *Forests*, **6**, 1982-2013. CrossRef

Tanré, D., Deroo, C., Duhaut, P., Herman, M., Morcrette, J.J., Perbos, J. & Deschamps, P.Y. (1990) Description of a Computer Code to Simulate the Satellite Signal in the Solar Spectrum: The 5S Code. *International Journal of Remote Sensing*, **11**, 659-668. CrossRef

Udelhoven, T., Stellmes, M. & Röder, A. (2015) Assessing rainfall-EVI relationships in the Okavango catchment employing MODIS time series data and distributed lag models. *Remote Sensing Time Series. Revealing Land Surface Dynamics* (ed. by C. Kuenzer, S. Dech and S. Wagner), pp. 225-245. Springer, Berlin, Heidelberg.

Van Niel, T.G. & McVicar, T.R. (2004) Determining Temporal Windows for Crop Discrimination with Remote Sensing: A Case Study in South-Eastern Australia. *Computers and Electronics in Agriculture*, **45**, 91-108. CrossRef

Verstraete, M.M., Hutchinson, C.F., Grainger, A., Stafford Smith, M., Scholes, R.J., Reynolds, J.F., Barbosa, P., Léon, A. & Mbow, C. (2011) Towards a global drylands observing system: Observational requirements and institutional solutions. *Land Degradation & Development*, **22**, 198-213. CrossRef

Woodcock, C.E., Allen, R., Anderson, M., Belward, A., Bindschadler, R., Cohen, W., Gao, F., Goward, S.N., Helder, D. & Helmer, E. (2008) Free Access to Landsat Imagery. *Science*, **320**, 1011a. CrossRef

Wulder, M.A., White, J.C., Goward, S.N., Masek, J.G., Irons, J.R., Herold, M., Cohen, W.B., Loveland, T.R. & Woodcock, C.E. (2008) Landsat Continuity: Issues and Opportunities for Land Cover Monitoring. *Remote Sensing of Environment*, **112**, 955-969. CrossRef

Zhu, Z. & Woodcock, C.E. (2012) Object-Based Cloud and Cloud Shadow Detection in Landsat Imagery. *Remote Sensing of Environment*, **118**, 83-94. CrossRef

Zhu, Z. & Woodcock, C.E. (2014) Continuous Change Detection and Classification of Land Cover using all Available Landsat Data. *Remote Sensing of Environment*, **144**, 152-171. CrossRef

A radar- and LiDAR-based earth observation system for monitoring savanna woody structure in southern Africa

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Abstract: In southern Africa, landscapes are dominated by savannas, i.e., mixed tree-grass communities. These savannas are threatened by land clearing and degradation, as well as the densification of woody plants, a process known as bush encroachment. There is, however, very limited spatial information on woody cover distribution and changes. Here, we report on the development of an operational system designed to map and monitor woody vegetation cover at a regional scale. This system is based on the combined use of freely available airborne light detection and ranging (LiDAR) data and synthetic aperture radar (SAR) satellite imagery. The integration of these two datasets provides an effective solution for assessing woody fractional cover in southern Africa beyond the level of details and accuracy previously available. Woody fractional cover was mapped at a national scale for South Africa and Namibia in 2010 and 2015 at 1 ha (100 × 100 m) pixel size.

Resumo: Na África Austral, as paisagens são dominadas por savanas, isto é, por comunidades de herbáceas e de lenhosas. Estas são ameaçadas pelo desmatamento e a degradação da terra, mas também, em muitas áreas, pela densificação de espécies lenhosas, conhecida por *bush encroachment* (invasão de lenhosas). Existe, porém, informação espacial muito limitada sobre a distribuição e as alterações da cobertura de espécies lenhosas. Neste artigo, relatamos o desenvolvimento de um sistema operacional desenhado para mapear e monitorizar a cobertura vegetal lenhosa à escala regional. Baseia-se no uso combinado de dados aéreos da tecnologia LiDAR (*Light Detection and Ranging*) disponíveis gratuitamente, e de imagens de satélite de SAR (Radar de Abertura Sintética). A integração destes dois conjuntos de dados fornece uma solução eficaz para avaliar a distribuição da savana e cobertura fracionada de lenhosas no Sul de África, para além do nível de detalhe e precisão actualmente disponíveis. A cobertura de lenhosas foi mapeada à escala nacional para a África do Sul e Namíbia em 2010 e 2015, com o tamanho de pixel de 1 ha (100 × 100 m).

Introduction

Southern African landscapes are dominated by savannas, or mixed tree-grass communities with a woody cover varying between 10% and 70%, which occupy close to half of the land mass (Scholes, 1997). Savannas provide a large number of ecosystem services and goods to millions of predominantly poor, rural people (e.g., firewood, charcoal, grass, construction timber, edible fruits) (Shackleton et al., 2007; Fig. 1), host a unique suite of floral and animal biodiversity, and are the third largest biome in terms of contributions to the land carbon storage pool (Grace et al., 2006). Savannas are threatened in some regions by clearing for cultivation or degradation through timber and fuelwood extraction, but there is mounting scientific evidence of a global trend of increasing woody vegetation, or bush encroachment (Eamus & Palmer, 2007; Lehmann et al., 2009; Mitchard & Flindtrop, 2013), possibly driven by an atmospheric CO_2 level increase. Bush encroachment is a significant risk for livestock production (Skowno et al., 2017). Savannas are critical to food and energy security of rural communities, but their regional dynamics and sustainability remain largely unknown.

Information on woody cover variability across southern Africa savannas is available only from products developed globally, such as the 30 m global forest cover maps derived from LandSAT 7 ETM+ data (Hansen et al., 2013) or the 25 m ALOS PALSAR global forest/non-forest JAXA datasets (Shimada et al., 2014). These products were developed primarily to track tropical forest losses, and they largely underestimate the distribution of open forests (Bastin et al., 2017). As a result of the lack of

Figure 1: (a) Deciduous savannas in the South African Lowveld; (b) rural communities rely extensively on savanna goods for energy and food securities, including fuelwood; (c) subsistence cultivation; (d) grazing resources.

quantitative data on the distribution of and changes in southern Africa's woody vegetation component, regional authorities are unable to monitor, manage, and therefore use this resource sustainably. Here, we report on the development of an operational system designed to map and monitor woody vegetation cover at a national scale for South Africa and Namibia (Task205). This system is based on the combined use of airborne light detection and ranging (LiDAR) and synthetic aperture radar (SAR) satellite imagery.

LiDAR and SAR: 3D remote sensing technologies

Active remote sensing sensors such as LiDAR and SAR are highly suited for measuring woody vegetation structure because these systems penetrate the canopy foliage and interact with the vertical shrub/tree profile. LiDAR instruments use airborne lasers systems to produce detailed 3D point clouds depicting the vertical woody vegetation profile and the underlying ground (Fig. 2). The processing of the point cloud enables the derivation of a wide range of structural woody metrics such as canopy cover, height, volume, and biomass. The spatial coverage of airborne LiDAR data is generally limited, mainly because of the high cost of acquisition. SAR sensors, on the other hand, are hosted on satellite platforms and the data cover vast areas suitable for regional mapping. Naidoo et al. (2016) demonstrated that winter (low-moisture) L-band SAR images were more effective at mapping woody cover in deciduous southern African savannas than were optical Landsat data.

Woody vegetation mapping and monitoring system

The woody cover mapping system uses large tracks of high-resolution airborne LiDAR data that are acquired for planning and monitoring of infrastructure such as roads, railway lines and power lines, as well as conservation areas and commercial forest. The LiDAR data are processed to generate LiDAR-based woody cover maps with a 25 × 25 m pixel size and then use these as training and validation for predictive models (Random Forest models) to map woody cover using satellite SAR data. For national- and regional-scale mapping, the system used the JAXA 25 m L-band ALOS PALSAR backscatter annual mosaics produced for 2007–2010 and 2015–2016. Ample existing LiDAR data (Fig. 3) were collected from multiple providers at no cost (e.g., ESKOM, Peace Park Foundation, Southern Mapping Company) and processed to produce canopy height models. The mapping system architecture was designed to be flexible and integrates the following capabilities: (1) ingesting large amounts of LiDAR-based woody cover or biomass data; (2) ingesting SAR satellite and environmental data sets (e.g., rainfall or temperature, topography) as explanatory variables; (3) creating large amounts of training and validation samples from LiDAR data; (4) integrating machine

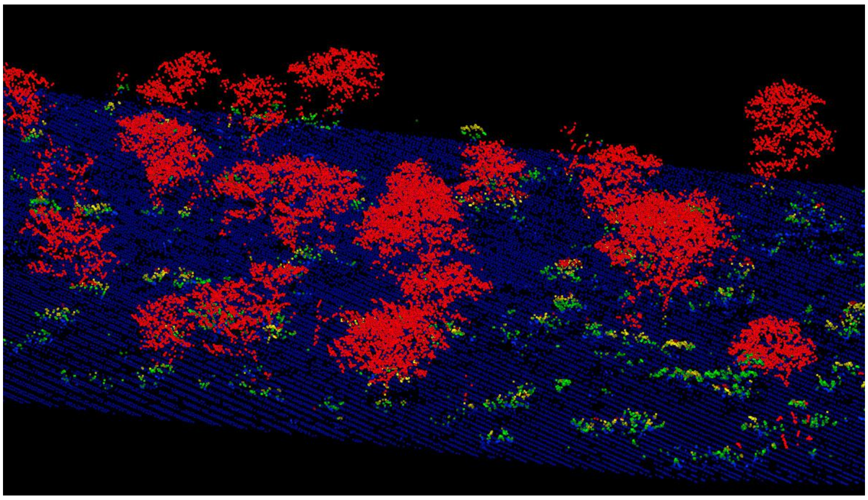

Figure 2: Example of LiDAR point cloud data for a typical savanna landscape in the South African Lowveld. Blue colours represent the ground, green and yellow colours represent shrubs, and orange and red colours represent small and tall trees, respectively.

learning models such as Random Forests, which learn from training samples in order to predict woody cover; (5) producing maps of cover and biomass at a user-defined pixel size (e.g., 25 m, 50 m, and 75 m resolution); and (6) validating the output maps with independent LiDAR data sets. Aggregation at larger pixel sizes reduces spatial details but decreases errors by averaging noise; the system therefore allows the user to select the scale at which the map will be produced. For more details on methods, see Main et al. (2016), Mathieu et al. (2013), Naidoo et al. (2015), Naidoo et al. (2016), and Urbazaev et al. (2015).

Outcome

Spatial patterns of woody vegetation

The regional patterns of woody vegetation cover were reliably mapped and correspond with the expected rainfall and vegetation type patterns (Fig. 4). Highest woody cover values are found in the eastern part of South Africa, where rainfall is the highest (following a north-to-south gradient from 350 to 1500 mm/year) and along the coast from Mozambique to Cape Town. Coastal forests are a mix of savannas, thickets, commercial plantations, patches of invasive alien plants (*Pinus* spp., *Eucaliptus* spp.), and remnants of dense indigenous forests. The Highveld in the South African central plateau is typically grassland and shows

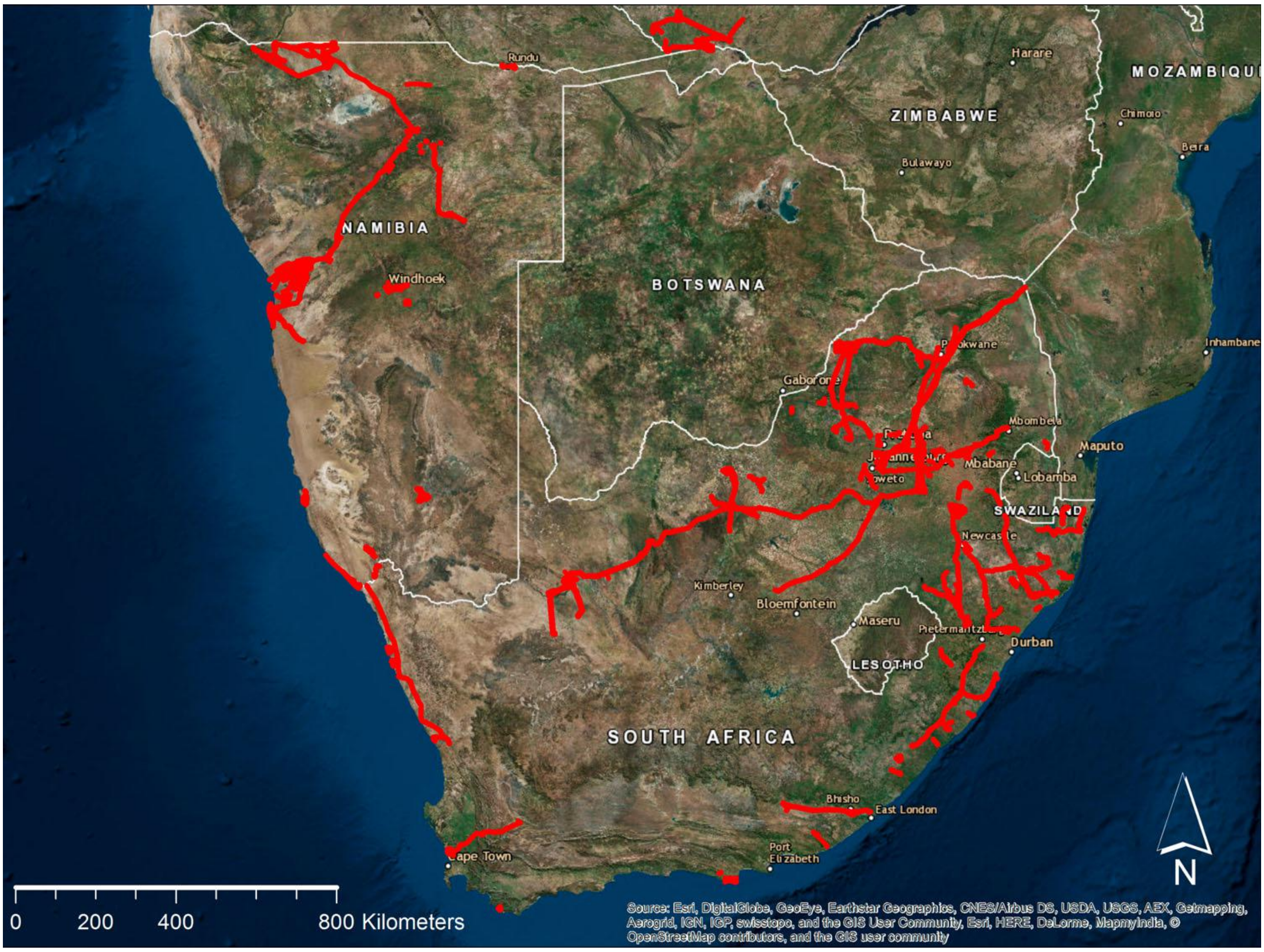

Figure 3: LiDAR coverage (red) amassed in southern Africa, including South Africa, Namibia, and Zambia. LiDAR data sets are sourced at no cost from a variety of providers including power utilities, conservation bodies, municipalities, and private plantations.

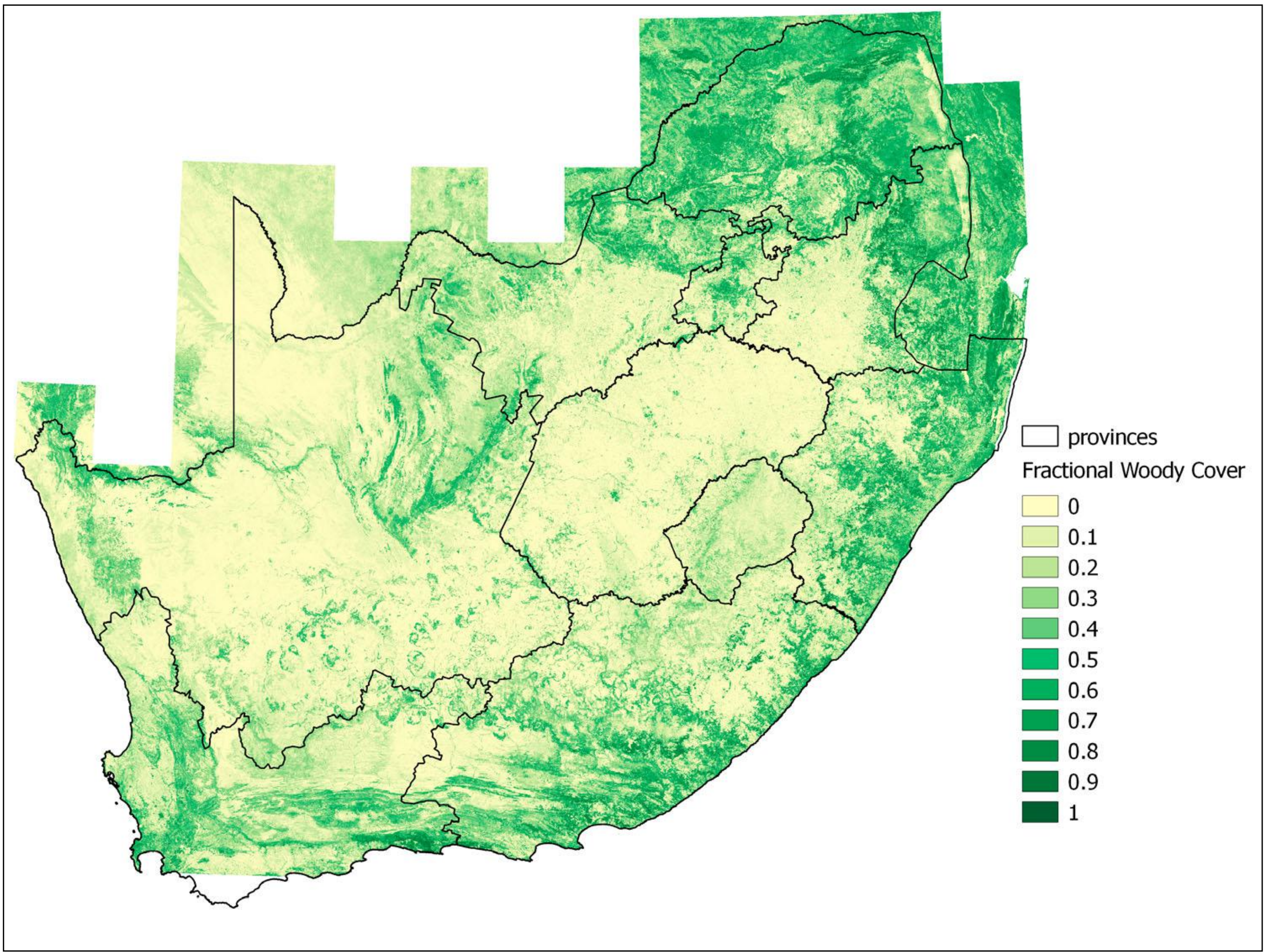

Figure 4: South African woody cover map produced from the predictive modelling exercise using airborne LiDAR and L-band ALOS PALSAR-2 mosaics acquired in 2010.

very low woody cover. The overall accuracy of the woody cover maps, expressed as coefficient of determination R^2, ranged from 0.64 to 0.76 for the 25 m to 75 m resolution. The corresponding root mean square error (RMSE) was 0.16 to 0.13, indicating an absolute fractional cover error of 16%–13%. Beyond the independent map validation with LiDAR data, field visits were conducted in South Africa and Namibia to investigate local scale patterns. Visual assessments found that significant details were captured (for example, natural variations across the landscape) in addition to management impacts such as fence-line contrasts. Although the backscatter of the ALOS PALSAR global mosaics were pre-processed to correct for terrain variation, the woody cover on steep slopes (steeper than 25%) was overestimated and will require additional processing or correction of topographic effects on backscatter. Aboveground biomass (AGB) maps were also produced in South Africa, but only for the savanna biome. The LiDAR-based AGB maps need to be calibrated with field AGB data acquired at the same time as the LiDAR imagery. Concurrent field data were available only for savanna vegetation, and thus could not yet be extended to the other regional vegetation types such as thicket or dense indigenous forests. This limitation is currently being addressed by CSIR, which is embarking on a large-scale field and airborne LiDAR campaign for a variety of vegetation types in South Africa, an undertaking that should lead to the development of national ABG maps in the near future.

Change detection

Woody cover change maps were calculated by subtracting an earlier woody cover map from a later map. Changes in commercial forestry (growth and clearing) areas were captured very effectively. In Namibia, large-scale debushing of bush encroached areas was easily detected (Fig. 5). Extensive burned areas as a result of severe wildfires also caused detectable reductions in woody cover. An increase in woody cover was most prevalent in historically debushed areas. Banding effects were present in the woody cover products retrieved from the global 2015 ALOS PALSAR mosaics. These stripes result from having constructed the mosaic with single ALOS PALSAR scenes acquired at different seasons and with variable scene moisture or leaf conditions. They complicate the detection of gradual changes linked to long-term bush encroachment. Overall, the project successfully demonstrated that the system can map and monitor woody vegetation in dryland savannas in order to inform policy and management initiatives, such as Namibia's Debushing Advisory Service and National Rangeland Management Policy and Strategy, or South Africa's Working for Ecosystems programme and State of Forests report.

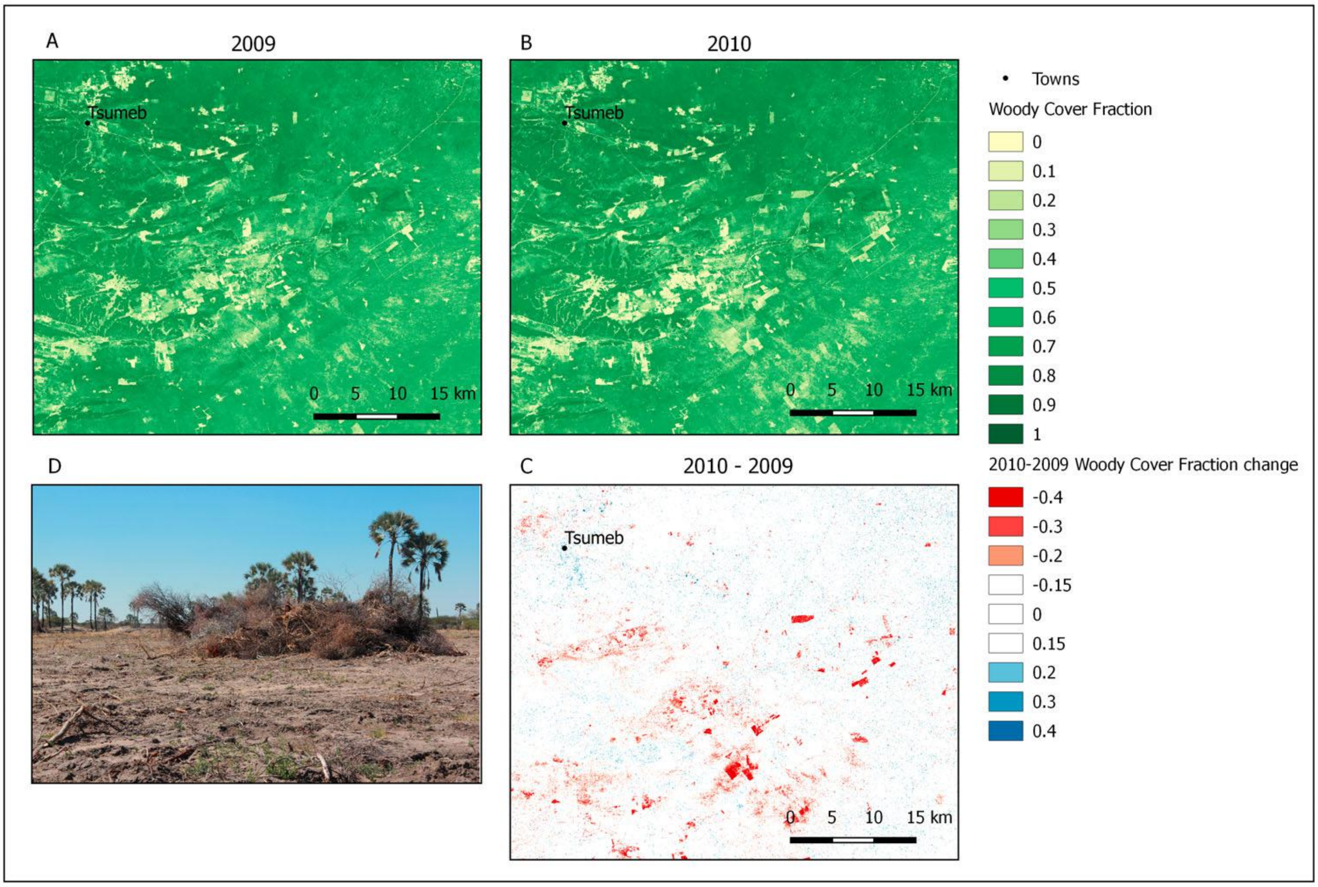

Figure 5: Woody cover fraction mapped with ALOS PALSAR data for (a) 2009, (b) 2010 and (c) the change between 2010 and 2009 in woody cover fraction near the town of Tsumeb in Namibia; (d) example of extensive debushing in north-eastern Namibia.

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References

Bastin, J., Berrahmouni, N., Grainger, A. et al. (2017) The extent of forest in dryland biomes. *Science*, **356**, 635-638.

Eamus, D. & Palmer, A.R. (2007) Is climate change a possible explanation for woody thickening in arid and semi-arid regions? *Research Letters in Ecology,* Article ID 37364.

Grace, J., San Jose, J., Meir, P., Miranda, H.S. & Montes, R.A. (2006) Productivity and carbon fluxes of tropical savannas. *Journal of Biogeography*, **33**, 387–400.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. & Townshend, J.R.G. (2013) High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, **342**, 850–853.

Lehmann, C.E.R., Prior, L.D. & Bowman, D.M.J.S. (2009) Decadal dynamics of tree cover in an Australian tropical savanna. *Austral Ecology,* **34**, 601–612.

Main, R., Mathieu, R., Kleynhans, W., Wessels, K., Naidoo, L. & Asner, G.P. (2016) Hyper-temporal C-band SAR for baseline woody structural assessments in deciduous savannas. *Remote Sensing*, **8**, 661.

Mathieu, R., Naidoo, L., Cho, M.A., Leblon, B., Main, R., Wessels, K., Asner, G.P., Buckley, J., Van Aardt, J., Erasmus, B.F.N. & Smit, I.P.J. (2013) Toward structural assessment of semi-arid African savannahs and woodlands: The potential of multitemporal polarimetric RADARSAT-2 fine beam images. *Remote Sensing of Environment*, **138**, 215–231.

Mitchard, E.T.A. & Flintrop, C.M. (2013) Woody encroachment and forest degradation in sub-Saharan Africa's woodlands and savannas, 1982–2006. Phil*osophical Transactions of the Royal Society B: Biological Sciences,* **368**, 20120406**.**

Naidoo, L., Mathieu, R., Main, R., Kleynhans, W., Wessels, K., Asner, G. & Leblon, B. (2015) Savannah woody structure modelling and mapping using multi-frequency (X-, C- and L-band) synthetic aperture radar data. *ISPRS Journal of Photogrammetry and Remote Sensing*, **105**, 234–250.

Naidoo, L., Mathieu, R., Main, R., Wessels, K. & Asner, G.P. (2016) L-band synthetic aperture radar imagery performs better than optical datasets at retrieving woody fractional cover in deciduous, dry savannahs. *International Journal of Applied Earth Observation and Geoinformation*, **52**, 54–64.

Scholes, R.J. (1997) Savanna. Vegetation of Southern Africa. Cambridge University Press, Cambridge, 258-277.

Shackleton, C.M., Shackleton, S.E., Buiten, E. & Bird, N. (2007) The importance of dry woodlands and forests in rural livelihoods and poverty alleviation in South Africa. *Forest Policy and Economics*, **9**, 558–577.

Shimada, M., Itoh, T., Motooka, T., Watanabe, M., Shiraishi, T., Thapa, R. & Lucas, R. (2014) New global forest/non-forest maps from ALOS PALSAR data (2007–2010). *Remote Sensing of Environment*, **155**, 13–31.

Skowno, A.L., Thompson, M.W., Hiestermann, J., Ripley, B., West, A.G. & Bond, W.J. (2017) Woodland expansion in South African grassy biomes based on satellite observations (1990–2013): general patterns and potential drivers. *Global Change Biology*, **23**, 2358–2369.

Urbazaev, M., Thiel, C., Mathieu, R., Naidoo, L., Levick, S.R., Smit, I.P.J., Asner, G.P. & Schmullius, C. (2015) Assessment of the mapping of fractional woody cover in southern African savannas using multi-temporal and polarimetric ALOS PALSAR L-band images. *Remote Sensing of Environment,* **166**, 138–153.

References [CrossRef]

Bastin, J., Berrahmouni, N., Grainger, A. et al. (2017) The extent of forest in dryland biomes. *Science*, **356**, 635-638. CrossRef

Eamus, D. & Palmer, A.R. (2007) Is climate change a possible explanation for woody thickening in arid and semi-arid regions? *Research Letters in Ecology*, Article ID 37364.

Grace, J., San Jose, J., Meir, P., Miranda, H.S. & Montes, R.A. (2006) Productivity and carbon fluxes of tropical savannas. *Journal of Biogeography*, **33**, 387–400. CrossRef

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. & Townshend, J.R.G. (2013) High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, **342**, 850–853. CrossRef

Lehmann, C.E.R., Prior, L.D. & Bowman, D.M.J.S. (2009) Decadal dynamics of tree cover in an Australian tropical savanna. *Austral Ecology*, **34**, 601–612. CrossRef

Main, R., Mathieu, R., Kleynhans, W., Wessels, K., Naidoo, L. & Asner, G.P. (2016) Hyper-temporal C-band SAR for baseline woody structural assessments in deciduous savannas. *Remote Sensing*, **8**, 661. CrossRef

Mathieu, R., Naidoo, L., Cho, M.A., Leblon, B., Main, R., Wessels, K., Asner, G.P., Buckley, J., Van Aardt, J., Erasmus, B.F.N. & Smit, I.P.J. (2013) Toward structural assessment of semi-arid African savannahs and woodlands: The potential of multitemporal polarimetric RADARSAT-2 fine beam images. *Remote Sensing of Environment*, **138**, 215–231. CrossRef

Mitchard, E.T.A. & Flintrop, C.M. (2013) Woody encroachment and forest degradation in sub-Saharan Africa's woodlands and savannas, 1982–2006. Philo*sophical Transactions of the Royal Society B: Biological Sciences*, **368**, 20120406**.** CrossRef

Naidoo, L., Mathieu, R., Main, R., Kleynhans, W., Wessels, K., Asner, G. & Leblon, B. (2015) Savannah woody structure modelling and mapping using multi-frequency (X-, C- and L-band) synthetic aperture radar data. *ISPRS Journal of Photogrammetry and Remote Sensing*, **105**, 234–250. CrossRef

Naidoo, L., Mathieu, R., Main, R., Wessels, K. & Asner, G.P. (2016) L-band synthetic aperture radar imagery performs better than optical datasets at retrieving woody fractional cover in deciduous, dry savannahs. *International Journal of Applied Earth Observation and Geoinformation*, **52**, 54–64. CrossRef

Scholes, R.J. (1997) Savanna. Vegetation of Southern Africa. Cambridge University Press, Cambridge, 258-277.

Shackleton, C.M., Shackleton, S.E., Buiten, E. & Bird, N. (2007) The importance of dry woodlands and forests in rural livelihoods and poverty alleviation in South Africa. *Forest Policy and Economics*, **9**, 558–577. CrossRef

Shimada, M., Itoh, T., Motooka, T., Watanabe, M., Shiraishi, T., Thapa, R. & Lucas, R. (2014) New global forest/non-forest maps from ALOS PALSAR data (2007–2010). *Remote Sensing of Environment*, **155**, 13–31. CrossRef

Skowno, A.L., Thompson, M.W., Hiestermann, J., Ripley, B., West, A.G. & Bond, W.J. (2017) Woodland expansion in South African grassy biomes based on satellite observations (1990–2013): general patterns and potential drivers. *Global Change Biology*, **23**, 2358–2369. CrossRef

Urbazaev, M., Thiel, C., Mathieu, R., Naidoo, L., Levick, S.R., Smit, I.P.J., Asner, G.P. & Schmullius, C. (2015) Assessment of the mapping of fractional woody cover in southern African savannas using multi-temporal and polarimetric ALOS PALSAR L-band images. *Remote Sensing of Environment*, **166**, 138–153. CrossRef

Land cover dynamics

Long-term land use change analysis in south-central Angola. Assessing the trade-off between major ecosystem services with remote sensing data

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Abstract: Dry tropical forests are facing large-scale conversion and degradation processes and are the most endangered forest type worldwide. We analyse these processes in the dry tropical forest type of miombo woodlands in a rural area of south-central Angola. We show that large-scale conversion to agricultural areas takes place in this area, as does modification of woodland areas, i.e. by degradation due to the extraction of natural resources. By using remote sensing data, spatial drivers of this conversion and its effects may be assessed for the time period 1989–2013. We identify settlement dynamics and the location and quality of streets as major underlying determining factors for conversion processes. Since the 1980s, the rate of agricultural expansion has strongly depended on socioeconomic background factors and is currently on a level of ca. 9 000 ha/year in the study area. Fallows were found to only slowly regenerate, and there is a change in cultivation pattern to more permanent forms of cultivation. Large portions of the study area are undergoing degradation processes, leading to an additional loss of biomass. The results indicate that there is high pressure on the natural ecosystems of the study area, which will probably aggravate in the future with a high likelihood of emerging land use conflicts.

Resumo: As florestas tropicais secas enfrentam processos de conversão e degradação de larga escala, sendo o tipo de floresta mais ameaçado mundialmente. Analisámos estes processos em bosques de Miombo (tipo de floresta tropical seca) numa área rural do centro Sul de Angola. Mostramos que ocorrem processos de conversão de grande escala para áreas agrícolas, bem como modificação de áreas de bosque, i.e., degradação devido à extracção de recursos naturais. Com recurso ao uso de dados de detecção remota, os factores espaciais desta conversão e os seus impactos puderam ser avaliados para o período de 1989 a 2013. Identificámos que as dinâmicas das povoações e a localização e qualidade das ruas são factores fundamentais, determinantes e subjacentes para os processos de conversão. Desde a década de 1980 que a taxa de expansão agrícola depende fortemente do contexto socioeconómico, estando actualmente a um nível de cerca de 9000ha/ano na área de estudo. Foi observado que os terrenos em pousio apenas regeneram lentamente, e há uma mudança no padrão de cultivo para formas de agricultura mais permanentes. Grandes zonas da área de estudo passam por processos de degradação, levando a uma perda adicional de biomassa. Os resultados indicam que existe uma alta pressão nos ecossistemas naturais da área de estudo, a qual irá provavelmente agravar no futuro com uma grande probabilidade de conflictos emergentes relacionados com o uso das terras.

Introduction

The conversion of forest to cultivation areas can be considered one of the main land use change processes of our time, and dry tropical forests, considered the most endangered forest type worldwide, are facing particularly massive conversion and degradation processes (Janzen, 1988; MEA, 2005). In Sub-Saharan Africa, the rapid rate of land conversion to agriculture can be attributed to a lack of modern farming techniques, e.g. fertilisation (MEA, 2005). This is also the predominant process witnessed in the miombo woodlands that stretch from the western coast of Angola to near the eastern coast of Mozambique and extend north-eastwards

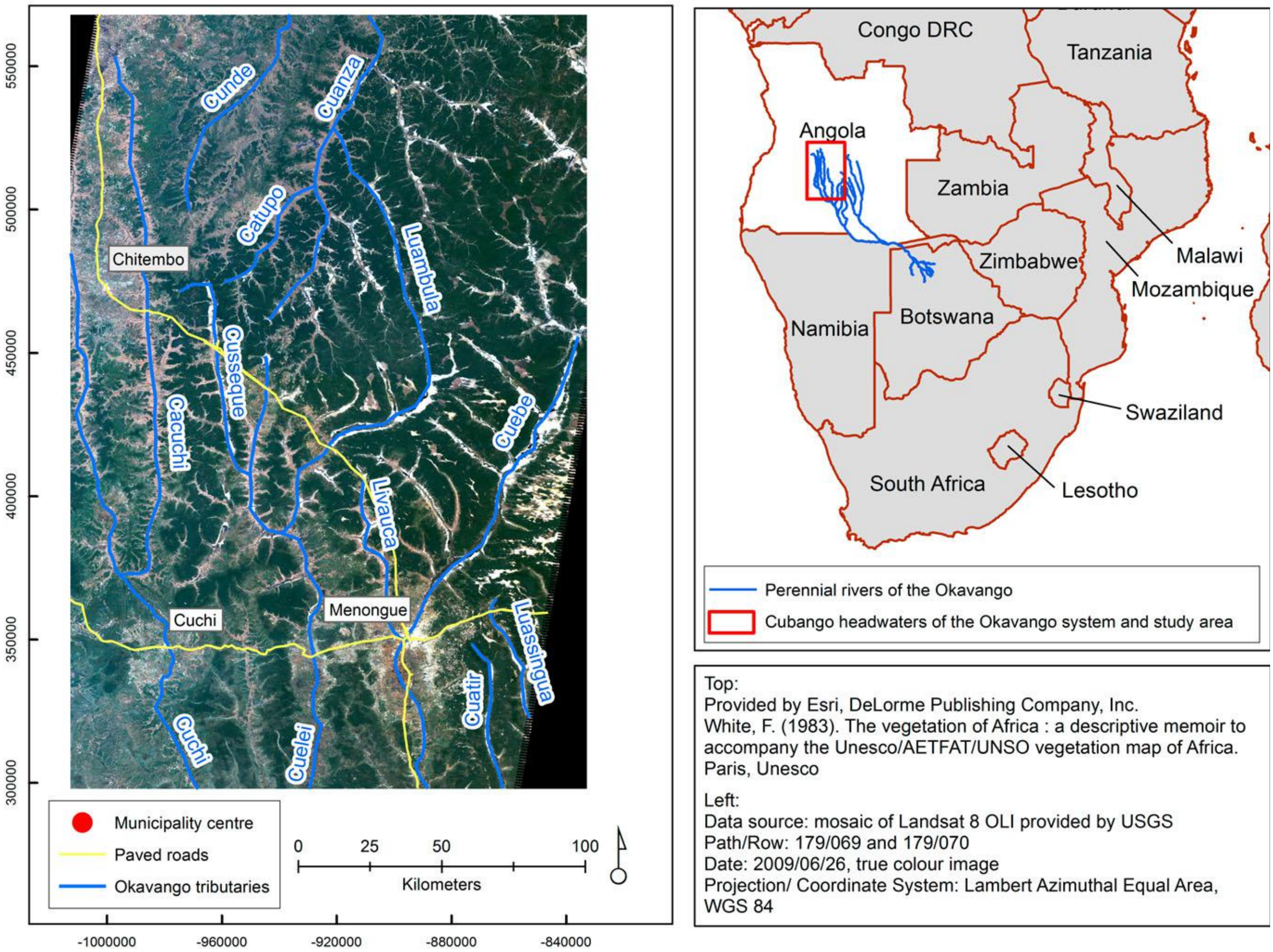

Figure 1: Overview of the study area, including the municipality administrations of Chitembo, Cuchi, and Menongue, as well as the main paved roads and areas of cultivation.

into Tanzania (Chidumayo & Gumbo, 2010). The largest proportion of miombo woodlands are located in Angola, and are of no interest to industrial logging. However, transformation and conversion processes due to smallholder agriculture, use of plants, charcoal and honey production, and the predicted investments of large-scale agricultural production put significant pressure on miombo ecosystems and have already reached the borders of sustainability (Dewees et al., 2010; Piedade, 2013; Finckh, 2015; Muzima & Mendy, 2015). This is partly due to the history of the country, as Angola still struggles with food shortages and insufficient medical and educational supply, as well as the ongoing reconstruction of infrastructure after 27 years of civil war.

The government of Angola was and is still confronted with infrastructure construction and demining issues, as well as with much-needed improvements to basic medical and educational services, especially in rural areas (BTI, 2014). Thus, the local population is still heavily dependent on the consumption of natural resources and subsistence agriculture. Currently, food is predominantly produced at the expense of woodland ecosystems by converting them to new fields; this process is presently indispensable to provide a basic food supply for human livelihood (Friis & Reenberg, 2010). On one hand, this leads to many areas of miombo woodlands being converted for cultivation purposes, but on the other hand to degradation processes due to the selective use of woodland resources (Piedade, 2013).

Providing a synthesis of a number of studies, we analyse processes of conversion and modification of miombo woodlands and assess the predominant trade-off between food production from agriculture and timber resource extraction. The two spheres, agricultural area and woodlands, are temporally and spatially analysed. Overall, the study objectives are as follows:

- to describe the temporal and spatial dynamics of agricultural expansion and the loss of miombo woodlands and quantify the trade-off between timber extraction and agricultural food production.
- to analyse changes in cultivation patterns and connect them to socioeconomic settings.
- to spatially and temporally describe woodland degradation processes.

Study area

The study area is located in south-central Angola and incorporates parts of the provinces of Bié, Cuando Cubango, and Moxico, covering an area of 48 600 km². The mean altitude is about 1 500 m above sea level (a.s.l.), ranging from 1 350 m a.s.l. in the wetlands to approx. 1 650 m a.s.l. in the hills (Fig. 1).

The study area is characterised by a large network of rivers that stretch from north to south with lateral valleys crossing the woodlands, which are situated on higher slopes and hilltops. At the centre of the valleys, wetlands with thick peat layers occur due to the constant inflow from the slopes. The soils of the slopes are predominantly Arenosols or shallow soils on granitic bedrock. The hilltops are covered by woodlands and also consist of Arenosols with medium concentration of nutrients (Gröngröft et al., 2013). The woodlands are characterised as open to dense miombo woodlands and are dominated by species of the genera *Brachystegia, Cryptosepalum,* and *Julbernadia*. Most of the geoxylic grasslands on the slopes are dominated by dwarf shrubs, particularly *Cryptosepalum maraviense* and *C. exfoliatum* spp. *suffruticans* and tall growing grasses (Revermann et al., 2013).

Methods

The presented work consists of several studies that were combined to answer the objectives formulated above. In each of these studies, multi-temporal and time series approaches were applied using satellite images provided by the Landsat sensor family. The Landsat-TM, -ETM+, and OLI sensors all have a medium resolution (30 x 30 m) and a regular monitoring frequency (up to 16 days), thus providing detailed and consistent information on land cover and land ecosystem changes for up to 35 years of history, which forms an ideal database for environmental monitoring at large (Wulder et al., 2008; Wulder et al., 2012). We make use of a pre-processing framework that provides radiometrically corrected Landsat images organised in a tiling structure that allows for efficient data access, which has been described in more detail by Röder et al. (this volume).

Agricultural expansion and trade-offs

In a first step, the impact of infrastructure reconstruction and improvement was assessed by using a bi-temporal unsupervised classification approach (1997/1998–2008/2009) based on Landsat data in combination with higher-resolution RapidEye data (Schneibel et al., 2013). For this purpose, an unsupervised classification using the ISODATA clustering algorithm was calculated on Landsat images from 1997/1998 as well as 2008/2009. The results of this classification were iteratively grouped based on aerial imagery using RapidEye data as reference. This resulted in a land use classification including the fields that were established between the two time steps. Additionally, roads and dirt tracks were captured and the locations of fields were analysed according their proximity to the streets by using a buffer analysis around both types of roads: paved and dirt tracks.

In a second step, the exact location of deforestation due to agricultural expansion was established for a larger study area and in higher temporal detail (Schneibel et al., 2016). This multi-temporal approach, again based on an unsupervised ISODATA algorithm, was also used to quantify the trade-off between food (maize) and timber by applying indicator values based on literature values (Chidumayo, 2014) as well as on household surveys. We could thus quantify the amount of maize grains (103 ± 54.1 kg ha^{-1}) that could potentially be harvested from the new fields that were established during one time step. In contrast, we could also denominate timber biomass (79.9 ± 11.05 t ha^{-1}) that was lost due to slash-and-burn activity for each time step (for the whole study period 1989–2013). The time steps ranged between 4–6 years, depending on data availability (see Fig. 3 for time step definition). Regeneration of biomass on fallows was also assessed by using the enhanced vegetation index (EVI) and stratification of the study area with spectral angle mapping (Schneibel et al., 2016). The EVI is a spectral index that is considered to be robust against background cover; its values do not saturate in dense vegetation areas (Huete et al., 2002). We calculated the EVI based on a 2014 Landsat image for those areas that were detected as new field areas in any of the time steps. For comparison reasons, we also calculated the mean EVI for 300 random points in woodland areas that could be considered as stable throughout the whole study period.

Cropping patterns

Although previous studies allowed the accurate delineation of agricultural fields and permitted analysis of the main drivers of agricultural expansion, we included a further study to focus on the temporal dynamics of field expansion and cultivation patterns (Schneibel et al., 2017a). We used an algorithm for temporal segmentation of annual Landsat time series (LandTrendr, Kennedy et al., 2010) from 1989 until 2013, which led to a temporally detailed analysis of cultivation dynamics. The LandTrendr algorithm automatically builds a time series based on a previously defined index. We chose the normalised burn ration (NBR) because it was most precise in detecting disturbances caused by the clearcutting of miombo woodland. LandTrendr provides pixel-based automatic selection of best observations according to the optimal phenological season via the day of the year and the absence of cloud cover. It uses the concept of time series segmentation and can detect both short- and long-term changes and yet is robust against intra-annual variations. For a detailed description of the LandTrendr approach, please see Kennedy et al. (2010). Outcome of the LandTrendr segmentation was a fitted time series that showed long-term trends as well as abrupt changes. To interpret this fitted time series, we only analysed those zones that were detected as agricultural areas in the previous studies. We used several parameters to interpret the fitted time series, adapted to the specific study area characteristics. The parameters were based on results from household surveys and resemble the known cultivation characteristics (e.g., onset of disturbance, length of disturbance, magnitude of disturbance). As a result, we were able to quantify onset, duration, and regeneration on an annual basis

Forest degradation

Whereas the previous studies primarily focused on the conversion process from woodland to agricultural areas, we complemented these in a last step by also analysing subtle modification processes occurring from 1989 until 2013 (Schneibel et al., 2017b). These processes, often

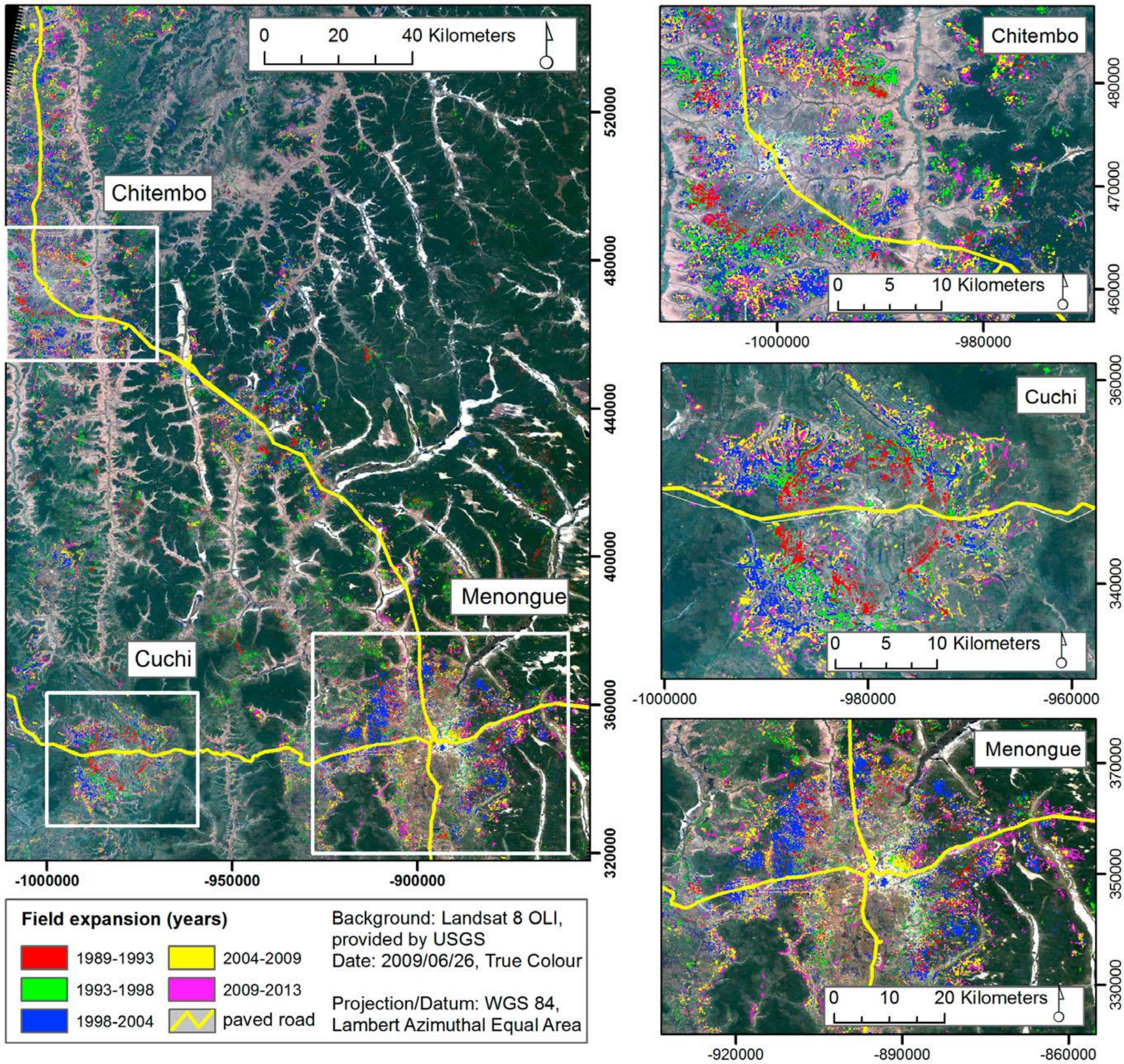

Figure 2: Agricultural expansion based on unsupervised classification (ISODATA) of Landsat data for five time steps. The different colours represent the different time steps. A close-up look for the cities Chitembo, Cuchi, and Menongue is also provided (right). The two paved roads are shown in yellow (Schneibel et al., 2016).

taking the form of degradation, were mainly due to selective logging for timber use, charcoal production, or honey production. For this purpose, the disturbance index (DI) was applied to a Landsat annual time series. The DI is a linear transformation of the Tasseled Cap indices (Kauth & Thomas, 1976) and is based on the assumption that disturbances will result in higher brightness and lower greenness and wetness values (Healey et al., 2005). The index minimises external influences like inter-annual variation of rainfall by rescaling the index via image statistics (mean and standard deviation of reference woodland population). The corresponding time series was analysed on a per-pixel basis by linear regression and parameters including intercept, significance of trend, mean absolute error, and maximum residuum were obtained. These parameters can be attributed to processes like previous use or disturbance, as well as different degradation or regeneration processes. Based on the parameters, the study area was classified into different degradation and regeneration areas, as well as stable woodland areas. To identify the impact of fire, MODIS ignition points were used for the time from 2000–2012 to assess spatial correspondence between fires and woodland degradation areas (Frantz et al., 2016).

Results

Agricultural expansion and trade-offs

The spatial delineation of fields shows agricultural expansion for five time steps and is illustrated in Figure 2. We found that expansion is spatially concentrated around roads and settlements and depends on the quality of streets (Fig. 2). Proportionally, the improvement (pavement) of a street led to a strong increase in agricultural areas being established in close proximity.

Regarding the temporal dynamics, a constant increase in the rate of agricultural

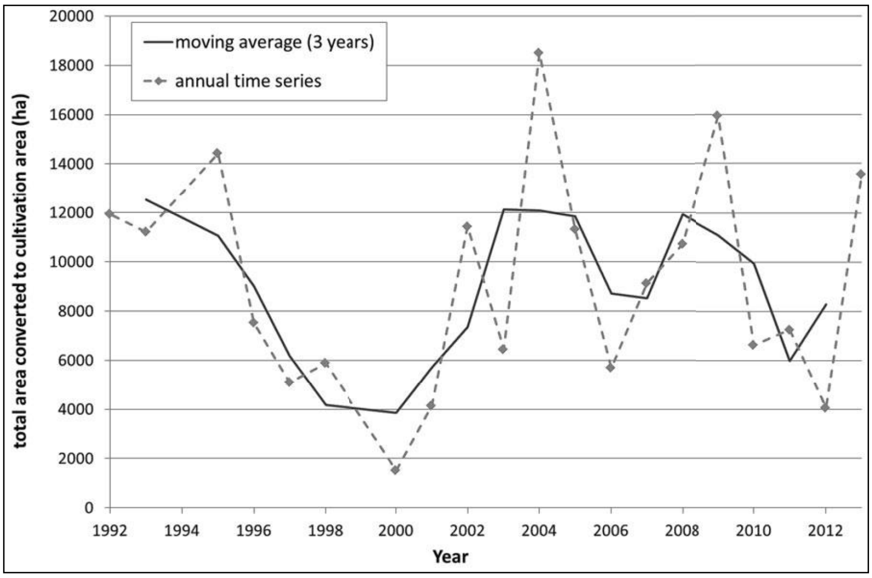

Figure 3: Annual area (ha) that is changed to agriculture (dotted line), including moving average for three years (straight line) (Schneibel et al., 2016).

expansion was detected over the five time steps for the whole study area (Schneibel et al., 2016). Nevertheless, the detailed analysis of annual time series shows specific temporal dynamics (Schneibel et al., 2017a) (Fig. 3). The rate of new fields after the nominal ceasefire period from 1994–1998 decreased from 12 000 ha per year to a minimum of 4 000 ha per year during the resumption of fighting from 1998–2002. Another maximum was reached shortly after the termination of the civil war; expansion in that period fluctuates heavily around 10 000 ha per year (Schneibel et al., 2017). Since 2004, expansion has decreased, which might be due to the changes in cultivation patterns from shifting to semi-permanent cultivation (Schneibel et al., 2016).

The rate of crop yield according to the conversion rate varied highly between farmers because of different soil types, farming techniques, or damage from insects or pests (103 ± 54.1 kg ha^{-1} of maize grains). Accordingly, this results in a highly variable overall available harvest. During the last several years, 1 200 tons of maize grains per year were available due to the large increase in agricultural area. For woodland biomass, the indicator value showed less variation, resulting in lower variabilities between a minimum of about 370 000 tons and a maximum of about 480 000 tons for the first time step. The loss of biomass also maximised for the last time step (2009–2013) with a mean of about 970 000 tons (Schneibel et al., 2016).

Cropping patterns

Although the main cultivation regime is shifting cultivation, the analysis of regrowth showed only slow regeneration. Regrowth was assessed for all areas that were detected as expanded agriculture. The EVI only provided an approximation to actual biomass cover. Regarding regrowth on former fields, it showed that from 1989 to 2013, the initial level of biomass was not reached again, which might be due to the relatively short recovery time period of 24 years. The highest EVI values were found in undisturbed woodlands, while the lowest EVI values occurred, as expected, on the most recently established fields (2009–2013) (Fig. 5) (Schneibel et al., 2016).

As biomass did not recover even in areas that are assumed to be mainly used for shifting cultivation, we also assessed if differences in cultivation patterns were visible within the study area. For the same observation time (1989–2013), the change from shifting to semi-permanent/permanent cultivation was evaluated. This change to more semi-permanent forms of cultivation was found when analysing regeneration of fields after the traditional cultivation time that was stated by the farmers in a household survey. Those fields that did not recover above a certain threshold after their assumed abandonment were regarded as being semi-permanent or permanent. This state was found for 22% of all fields in the study area; however, it holds especially true around the cities.

Forest degradation

In addition to the conversion processes of woodland to field, we also analysed woodland degradation processes. The following map (Fig. 5) shows that degradation processes are widespread not only around cities and infrastructure, but also in the presumably undisturbed woodland

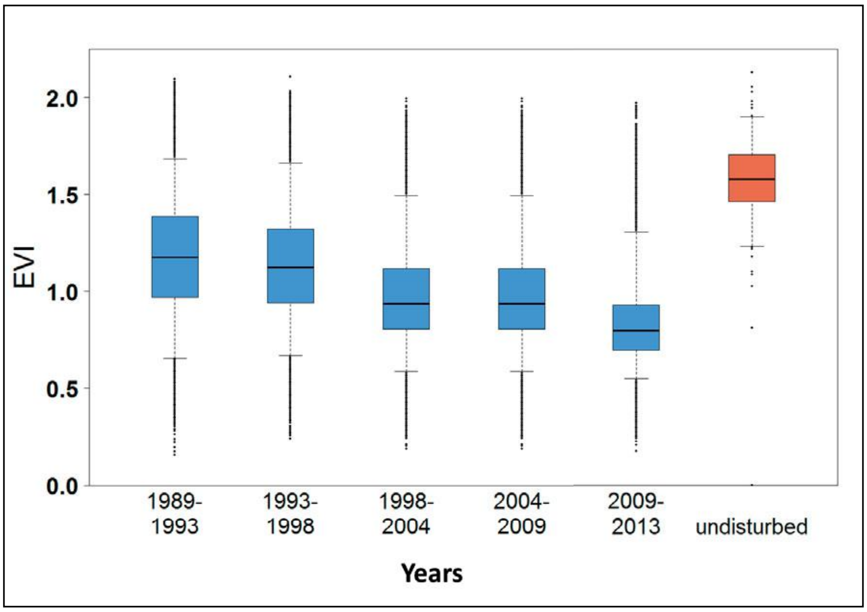

Figure 4: EVI values that relate to biomass regrowth for the five time steps. EVI values for undisturbed woodlands are displayed in red (Schneibel et al., 2017a).

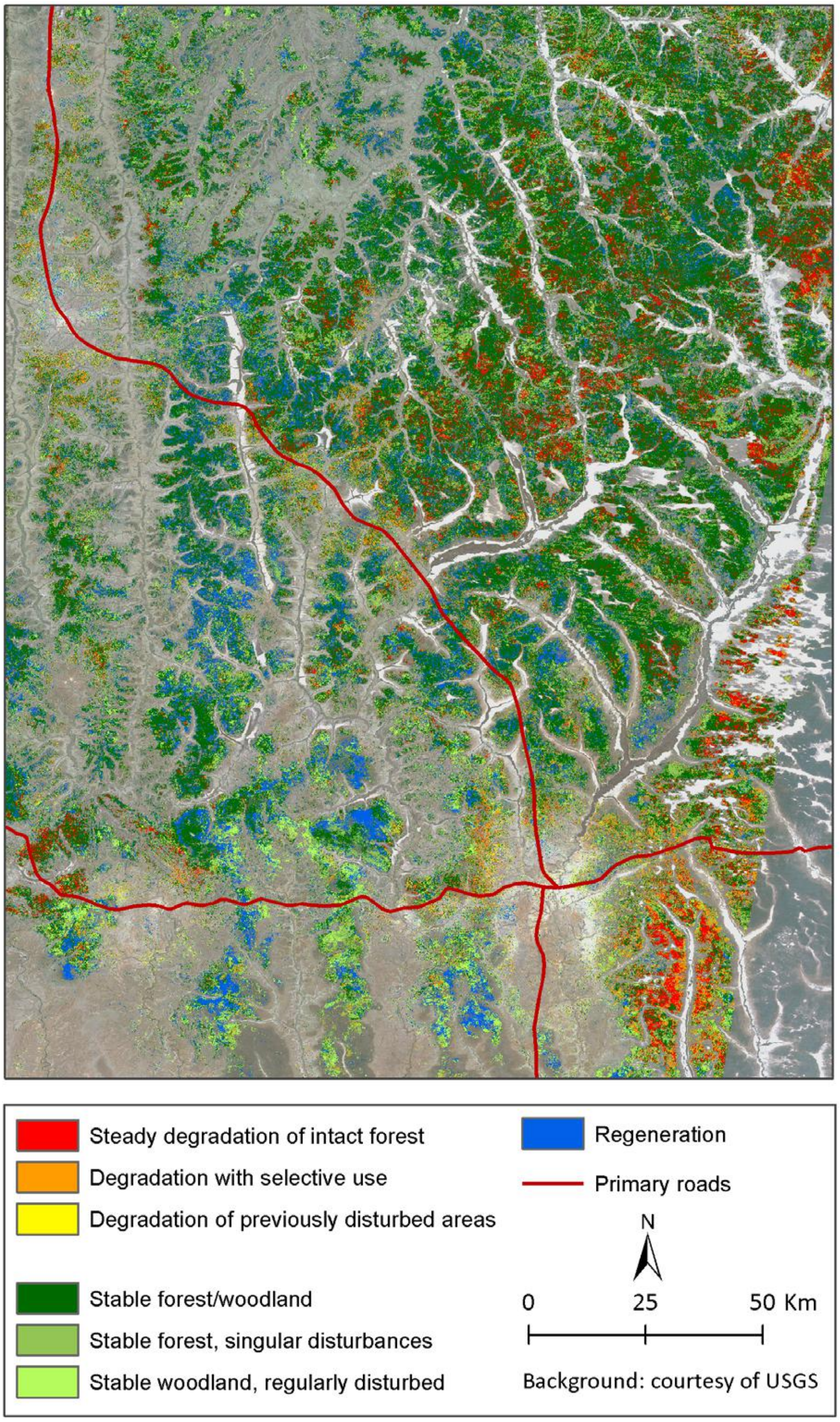

Figure 5: The map shows degradation processes within the miombo woodlands (red and pink colours) as well as regularly disturbed but stable woodlands (orange colours) and undisturbed woodland regions (green colours) for the time between 1989 and 2013 (Schneibel et al., 2017b).

areas in the eastern part of the study area. Nevertheless, almost 74% of the miombo woodlands did not show any significant conversion trend and could thus be considered undisturbed. Overall, 13.3% of woodlands showed degrading trends and almost the same proportion (12.8%) can be considered to be regenerating (Schneibel et al., 2016) (Fig. 5). Furthermore, we could identify regular disturbances (e.g., due to selective use) taking place in woodland areas. This information is based on the maximum residuum, leading to high short-term fluctuation in the time series.

The results were evaluated against MODIS ignition points. Although a quantitative assessment of spatial correlation was not possible due to different observation periods (2000–2013 for MODIS ignition points and 1989–2013 for the Landsat time series), there seems to be a relationship between regular fires and degradation areas.

Discussion

The trend of increasing deforestation must be evaluated in the context of socioeconomic changes and, in particular, increasing population numbers. When observing large-scale resettlement dynamics and population growth, it is not surprising that there is still a lack of available food supply, and thus a high demand for food (BTI, 2014). These resettlements primarily occurred during the civil war, due to people fleeing into the cities, seeking safety and basic supplies, but also to the government moving people closer to cities and to refugees returning after the final ceasefire. These dynamics can be seen in the rapid deforestation of miombo woodlands around the cities, especially after the ceasefire in 2002, as well as in a high number of early fields (1989–1998) that were established in the woodlands but given up around the civil war's termination.

Deforestation and cultivation patterns are connected to infrastructure destruction and reconstruction. The two main roads of the study area were reconstructed from 2008–2010. This enabled access to new woodland areas and, at the same time, to local trading hubs. Furthermore, after the civil war, former refugees were resettled by governmental orders close to streets and existing settlements. These resettlement actions, in combination with the increased safety of using woodland areas, might have affected the first wave of agricultural expansion from 2000–2004. Later decreases in the rate of agricultural expansion might be attributed to the life cycle of fields.

Our results showed that the cultivation cycle has been changing slowly from shifting cultivation to semi-permanent or permanent forms of cultivation. Household surveys of farmers showed that a lack of seeds, field input, and knowledge prevents them from adopting new production practices (Domptail et al., 2013). Especially around urban areas in which there is improved market access and higher population pressure, however, shifting cultivation seems to be in the process of being replaced by more permanent types of cultivation. This development follows a typical transition of tropical smallholder farming systems: from shifting cultivation to semi-permanent cultivation or permanent rain-fed cultivation (Ruthenberg et al., 1971). In the long term, this can result in decreased yields and degraded soils and is therefore considered an undesired form of intensification.

But even if a field lies fallow for decades, our evidence suggests that biomass is not recovering. This is in line with Chidumayo (2014), who explains that miombo woodlands rarely recover to their previous tree biomass due to the loss of root biomass that is caused by cutting, and also by recurring fires. Other authors indicate a relatively quick recovery of biomass after abandonment and a resilience of tree species diversity to clearing by shifting agriculture (McNicol et al., 2015), but this work does not contain any time series data to relate findings to the pre-disturbance state. The factor of recurring fires also played a major role in the study of woodland degradation, where potentially stable woodlands are regularly disturbed by fire events, although to a far lesser extent than occurs during woodland clearing. According to our results, many woodland areas are affected by fires, but these events seem to mainly affect the understorey.

The impact of woodland disturbance could not be considered in the trade-off analysis. Nevertheless, the calculation of maize yield and biomass loss gives an impression about the dimension of disturbance. Those numbers, however, have to be interpreted in light of the knowledge that maize can be harvested annually, while deforestation and the loss of woody biomass is a single-time action.

This trade-off will likely worsen in the future, because the prevalent global driving forces of degradation (e.g. commercialisation) (Geist & Lambin, 2002) are not yet dominant in rural Angola. We found that deforestation and agricultural expansion are strongly connected to population movements and the need for basic supply. This leads to a high dependency on the international food market and still-insufficient governmental food imports (World Bank, 2013). Additional underlying drivers of dry tropical forest disturbance and degradation, such as agricultural expansion, wood extraction, and infrastructural development (Geist & Lambin, 2002), are clearly applicable within the study area. Furthermore, commodification products like charcoal and honey will gain more importance in the region, yet their production also relies on the availability of woodland areas.

The effects of woodland conversion, changes in cultivation systems, and degradation illustrate that people are still highly dependent on natural resources, and thus must rely on sustainable management actions. The overall dynamics of deforestation and woodland degradation in the study area express the urgent need for a broader base of field data, for further spatial analysis of subtle and direct woodland cover loss, and for the integration of these results into studies that account for ecosystem service provision, like carbon budgeting programs. Remote sensing can contribute to these programs by delivering spatially and temporally consistent information on land cover change that can be conceptually connected to socio-economic and environmental field data to delineate current and future endangered areas.

Our studies demonstrate the potential of using operational earth observation data to address a variety of aspects of forest conversion and modification, and show how remote sensing-based results may bridge information gaps in areas with only sparse ground-based information. The advent of new waves of sensors, such the Sentinel program launched by the European Space Agency or the numerous micro-satellites that have emerged only recently, will provide increased monitoring and observation capabilities, while the Landsat data utilised for this study will continue to form the backbone for many long-term studies due to their historic legacy.

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References

BTI, B.S. (2014) Angola Country Report. In. Bertelsmann Stiftung, Gütersloh.

Chidumayo, E.N. (2014) Estimating tree biomass and changes in root biomass following clear-cutting of Brachystegia-Julbernardia (miombo) woodland in central Zambia. *Environmental Conservation*, **41**, 54–63.

Chidumayo, E.N. & Gumbo, D.J. (2010) *The dry forests and woodlands of Africa: Managing for products and services*. Earthscan, London.

Dewees, P.A., Campbell, B.M., Katerere, Y., Sitoe, A., Cunningham, A.B., Angelsen, A. & Wunder, S. (2010) Managing the miombo woodlands of southern Africa: Policies, incentives, and options for the rural poor. *Journal of Natural Resources Policy Research*, **2**, 57–73.

Domptail, S., Große, L. M., Kowalski, B., & Baptista, J. (2013). Cusseque/cacuchi—The people. *Biodiversity and Ecology*, **5**, 73–80.

Finckh, M., Pröpper, M., Autlwetse, B., et al. (2015) The current status of the Okavango Basin. *The Future Okavango: Findings, scenarios, and recommendations for action. Research project final synthesis report 2010–2015* (ed. by M. Pröpper, A. Gröngröft, M. Finckh, et al.), pp. 25–51. University of Hamburg--Biocentre Klein Flottbek, Hamburg, Germany.

Frantz, D., Stellmes, M., Röder, A. & Hill, J. (2016) Fire spread from MODIS burned area data: Obtaining fire dynamics information for every single fire. *International Journal of Wildland Fire*, **25**, 1228–1237.

Friis, C. & Reenberg, A. (2010) Land grab in Africa: Emerging land system drivers in a teleconnected world. *GLP Report*, **1.**

Geist, H.J. & Lambin, E.F. (2002) Proximate causes and underlying driving forces of tropical deforestation: Tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations. *BioScience*, **52**, 143–150.

Gröngröft, A., Luther-Mosebach, J., Landschreiber, L. & Eschenbach, A. (2013) Cusseque: Soils. *Biology & Ecology*, **5**, 4.

Healey, S.P., Cohen, W.B., Zhiqiang, Y. & Krankina, O.N. (2005). Comparison of tasseled cap-based Landsat data structures for use in forest disturbance detection. *Remote Sensing of Environment*, **97**, 301–310.

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X. & Ferreira, L.G. (2002) Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, **83**, 195–213.

Janzen, D.H. (1988) Tropical dry forests. *Biodiversity*, 538.

Kauth, R.J. & Thomas, G.S. (1976, January). The tasselled cap: A graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. In *LARS Symposia.*

Paper 159:4B41 – 4B51. https://docs.lib.purdue.edu/lars_symp/159/

Kennedy, R.E., Yang, Z., & Cohen, W.B. (2010). Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr—Temporal segmentation algorithms. *Remote Sensing of Environment*, **114**, 2897–2910.

McNicol, I.M., Ryan, C.M., & Williams, M. (2015). How resilient are African woodlands to disturbance from shifting cultivation? *Ecological Applications*, **25**, 2320–2336.

MEA. (2005) Living beyond our means: Natural assets and human well-being. *Statement of the MA Board*. Island Press, Washington, DC.

Muzima, J.D. & Mendy, F.R. (2015) Angola 2015. *African economic outlook 2015.* OECD Publishing, Paris.

Piedade, A.F. (2013) Cusseque: Use of woody plants. *Biodiversity & Ecology,* **5**, 69–72.

Revermann, R., Maiato, F., Gomes, A., Lages, F. & Finckh, M. (2013) Cusseque: Vegetation. *Biodiversity & Ecology,* **5**, 59–64.

Röder, A., Stellmes, M., Frantz, D. & Hill, J. (2018) Remote sensing-based environmental assessment and monitoring: Generation of operational baseline and enhanced experimental products in southern Africa. This Volume.

Ruthenberg, H., MacArthur, J.D., Zandstra, H. & Collinson, M.P. (1971) *Farming systems in the tropics*. Cambridge University Press, Cambridge.

Schneibel, A., Stellmes, M., Revermann, R., Finckh, M., Röder, A. & Hill, J. (2013) Agricultural expansion during the post-civil war period in southern Angola based on bi-temporal Landsat dara. *Biodiversity & Ecology*, **5**, 311–319

Schneibel, A., Stellmes, M., Röder, A., Finckh, M., Revermann, R., Frantz, D. & Hill, J. (2016) Evaluating the trade-off between food and timber resulting from the conversion of miombo forests to agricultural land in Angola using multi-temporal Landsat data. *Science of the Total Environment*, **548**, 390–401.

Schneibel, A., Stellmes, M., Röder, A., Frantz, D., Kowalski, B., Haß, E. & Hill, J. (2017a) Assessment of spatio-temporal changes of smallholder cultivation patterns in the Angolan miombo belt using segmentation of Landsat time series. *Remote Sensing of Environment*, **195**, 118–129.

Schneibel, A., Frantz, D., Röder, A., Stellmes, M., Fischer, K. & Hill, J. (2017b). Using annual Landsat time series for the detection of dry forest degradation processes in south-central Angola. *Remote Sensing*, **9**, 905.

World Bank (2013). *Angola, economic update*. Issue 1. World Bank Enterprise Survey, Washington, DC.

Wulder, M.A., Masek, J.G., Cohen, W.B., Loveland, T.R. & Woodcock, C.E. (2012) Opening the archive: How free data has enabled the science and monitoring promise of Landsat. *Remote Sensing of Environment*, **122**, 2–10.

Wulder, M.A., White, J.C., Goward, S.N., Masek, J.G., Irons, J.R., Herold, M., Cohen, W.B., Loveland, T.R. & Woodcock, C.E. (2008) Landsat continuity: Issues and opportunities for land cover monitoring. *Remote Sensing of Environment*, **112**, 955–969.

References [CrossRef]

BTI, B.S. (2014) Angola Country Report. In. Bertelsmann Stiftung, Gütersloh.

Chidumayo, E.N. (2014) Estimating tree biomass and changes in root biomass following clear-cutting of Brachystegia-Julbernardia (miombo) woodland in central Zambia. *Environmental Conservation*, **41**, 54–63. CrossRef

Chidumayo, E.N. & Gumbo, D.J. (2010) *The dry forests and woodlands of Africa: Managing for products and services*. Earthscan, London.

Dewees, P.A., Campbell, B.M., Katerere, Y., Sitoe, A., Cunningham, A.B., Angelsen, A. & Wunder, S. (2010) Managing the miombo woodlands of southern Africa: Policies, incentives, and options for the rural poor. *Journal of Natural Resources Policy Research*, **2**, 57–73. CrossRef

Domptail, S., Große, L. M., Kowalski, B., & Baptista, J. (2013). Cusseque/cacuchi—The people. *Biodiversity and Ecology*, ***5***, 73–80. CrossRef

Finckh, M., Pröpper, M., Autlwetse, B., et al. (2015) The current status of the Okavango Basin. *The Future Okavango: Findings, scenarios, and recommendations for action. Research project final synthesis report 2010–2015* (ed. by M. Pröpper, A. Gröngröft, M. Finckh, et al.), pp. 25–51. University of Hamburg--Biocentre Klein Flottbek, Hamburg, Germany.

Frantz, D., Stellmes, M., Röder, A. & Hill, J. (2016) Fire spread from MODIS burned area data: Obtaining fire dynamics information for every single fire. *International Journal of Wildland Fire*, **25**, 1228–1237. CrossRef

Friis, C. & Reenberg, A. (2010) Land grab in Africa: Emerging land system drivers in a teleconnected world. *GLP Report*, **1.**

Geist, H.J. & Lambin, E.F. (2002) Proximate causes and underlying driving forces of tropical deforestation: Tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations. *BioScience*, **52**, 143–150. CrossRef

Gröngröft, A., Luther-Mosebach, J., Landschreiber, L. & Eschenbach, A. (2013) Cusseque: Soils. *Biology & Ecology*, **5**, 4. CrossRef

Healey, S.P., Cohen, W.B., Zhiqiang, Y., & Krankina, O.N. (2005). Comparison of tasseled cap-based Landsat data structures for use in forest disturbance detection. *Remote Sensing of Environment*, **97**, 301–310. CrossRef

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., & Ferreira, L.G. (2002) Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, **83**, 195–213. CrossRef

Janzen, D.H. (1988) Tropical dry forests. *Biodiversity*, 538.

Kauth, R.J., & Thomas, G.S. (1976, January). The tasselled cap: A graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. In *LARS Symposia*. Paper 159:4B41 – 4B51. https://docs.lib.purdue.edu/lars_symp/159/

Kennedy, R.E., Yang, Z., & Cohen, W.B. (2010). Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr—Temporal segmentation algorithms. *Remote Sensing of Environment*, **114**, 2897–2910. CrossRef

McNicol, I.M., Ryan, C.M., & Williams, M. (2015). How resilient are African woodlands to disturbance from shifting cultivation? *Ecological Applications*, **25**, 2320–2336. CrossRef

MEA. (2005) Living beyond our means: Natural assets and human well-being. *Statement of the MA Board*. Island Press, Washington, DC.

Muzima, J.D. & Mendy, F.R. (2015) Angola 2015. *African economic outlook 2015*. OECD Publishing, Paris.

Piedade, A.F. (2013) Cusseque: Use of woody plants. *Biodiversity & Ecology*, **5**, 69–72. CrossRef

Revermann, R., Maiato, F., Gomes, A., Lages, F. & Finckh, M. (2013) Cusseque: Vegetation. *Biodiversity & Ecology*, **5**, 59–64. CrossRef

Röder, A., Stellmes, M., Frantz, D. & Hill, J. (2018) Remote sensing-based environmental assessment and monitoring: Generation of operational baseline and enhanced experimental products in southern Africa. This Volume. CrossRef

Ruthenberg, H., MacArthur, J.D., Zandstra, H. & Collinson, M.P. (1971) *Farming systems in the tropics*. Cambridge University Press, Cambridge.

Schneibel, A., Stellmes, M., Revermann, R., Finckh, M., Röder, A., & Hill, J. (2013) Agricultural expansion during the post-civil war period in southern Angola based on bi-temporal Landsat dara. *Biodiversity & Ecology*, **5**, 311–319. CrossRef

Schneibel, A., Stellmes, M., Röder, A., Finckh, M., Revermann, R., Frantz, D. & Hill, J. (2016) Evaluating the trade-off between food and timber resulting from the conversion of miombo forests to agricultural land in Angola using multi-temporal Landsat data. *Science of the Total Environment*, **548**, 390–401. CrossRef

Schneibel, A., Stellmes, M., Röder, A., Frantz, D., Kowalski, B., Haß, E. & Hill, J. (2017a) Assessment of spatio-temporal changes of smallholder cultivation patterns in the Angolan miombo belt using segmentation of Landsat time series. *Remote Sensing of Environment*, **195**, 118–129. CrossRef

Schneibel, A., Frantz, D., Röder, A., Stellmes, M., Fischer, K., & Hill, J. (2017b). Using annual Landsat time series for the detection of dry forest degradation processes in south-central Angola. *Remote Sensing*, **9**, 905. CrossRef

World Bank (2013). *Angola, economic update*. Issue 1. World Bank Enterprise Survey, Washington, DC.

Wulder, M.A., Masek, J.G., Cohen, W.B., Loveland, T.R. & Woodcock, C.E. (2012) Opening the archive: How free data has enabled the science and monitoring promise of Landsat. *Remote Sensing of Environment*, **122**, 2–10. CrossRef

Wulder, M.A., White, J.C., Goward, S.N., Masek, J.G., Irons, J.R., Herold, M., Cohen, W.B., Loveland, T.R. & Woodcock, C.E. (2008) Landsat continuity: Issues and opportunities for land cover monitoring. *Remote Sensing of Environment*, **112**, 955–969. CrossRef

Collaborative Postgraduate Programme in Applied Science in Earth Observation, Geographic Information Systems and Remote Sensing

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The challenge

Capacity-building in the Southern Africa Science Services Centre for Climate Change and Adaptive Land Management (SASSCAL) is an essential part of the initiative's science programme. One of the major capacity limitations identified at the Southern African Development Community (SADC) level is in the field of Earth Observation, Geographic Information Systems, and Remote Sensing. Within Task 303, a collaborative Master of Science degree in Geographic Information Systems, Remote Sensing, and Earth Observation was designed and implemented by four SADC universities: University of Botswana (UB), University of Zambia (UNZA), Cape Peninsula University of Science and Technology (CPUT, South Africa), and Namibia University of Science and Technology (NUST), the coordinating university.

The development of the core curriculum

Nominated members of the four universities developed the curriculum of the collaborative MSc jointly. They adopted a modified Developing a Curriculum (DACUM) process to identify minimum elements of the core curriculum. This process incorporates the use of a focus group in a facilitated storyboarding process to capture the major duties and related tasks included in an occupation, as well as the necessary knowledge, skills, and traits for success in the field. To address the needs of each partner, some specialisations based on their capacity and expertise were included. The process adopted proved effective in that it respected the various national regulations and internal university processes and procedures while also meeting the identified capacity needs in this field (Tab. 1).

The collaborative Master of Science Degree programme

Since the programme's implementation in May 2016, 45 students have been admitted at NUST, UB, and UNZA, 35 of whom are benefitting from SASSCAL Task 303 scholarships that fund tuition fees, stipends, medical insurance, travel and visa expenses, and a modest research grant.

In July 2016, the first programme was launched at NUST with an intake of 14 students. These students are now at the thesis stage and are expected to graduate in 2018 (Fig. 1).

The second programme, launched at UNZA in May 2017, has 22 students (Fig. 2); UB launched its programme in November 2017 and admitted nine students. Table 2 shows the intakes and country of origin of funded students at the three universities. Despite the language barrier and limited capacity to contribute to curriculum development, three Angolan students were admitted to the programme. The curriculum development process at CPUT was delayed due to internal restructuring of programmes but will hopefully be implemented within the next three years. In addition to scholarships, Task 303 also funded equipment; software; and personnel training, including faculty to teach and supervise students at participating universities. This has provided an excellent opportunity for students to benefit from a unique academic experience with an international flavour.

The Master of Science degree awarded will place graduates in a better position to undertake further postgraduate studies at the PhD level or seek employment in HEIs, research institutions and centres, government or non-governmental organisations, or the private (suitable professional) sector.

As one strategy to ensure that this Master of Science programme remains sustainable, the universities will continue to market and promote it to national and regional institutions and organisations. Beneficiary students will be branded SASSCAL alumni and will be an integral part of this promotion strategy.

Table 1: Curriculum structure at NUST, UB and UNZA, showing common and elective courses

Courses	NUST	UB	UNZA	Common (C) or Elective (E)
Advanced Image Processing and Interpretation	x	x	x	C
Advanced Research Methodology	x	x	x	C
Spatial Analytical Methods	x	x	x	C
Advanced Environmental Remote Sensing	x	x	x	C
Advanced Digital Photogrammetry	x			E
(Advanced) GIS for Spatial Planning	x			E
Advanced GIS Programming	x		x	E
Communication of Geospatial Information	x		x	E
Spatial Databases and Web Mapping	x			E
Management of Geospatial Information	x			E
Quantitative Techniques in Environmental Management		x		E
Integrated Environmental Management		x		E
Specialist Directed Readings & Labs		x		E
GIS Modelling & Data Management		x		E
Crop Yield Estimations and Early Warning Systems			x	E
Rapid Forest Assessment and Monitoring			x	E
Spatial Databases			x	E
Web Mapping and Geospatial Web Services			x	E
GIS for Hydrology and Water Resources			x	E
Mobile Computing for GIS			x	E

Figure 1: Launch of NUST programme in Windhoek, November 2016.

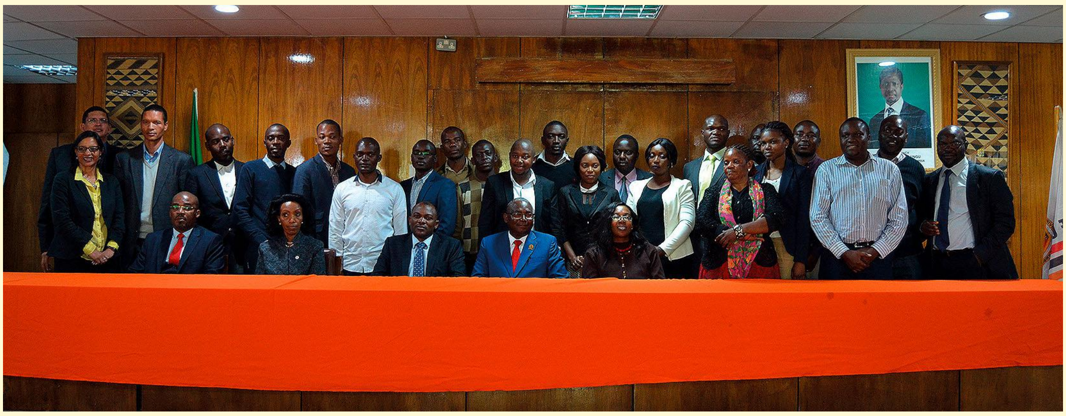

Figure 2: Launch of UNZA programme in Lusaka, May 2017.

Table 2: Intakes and country of origin of SASSCAL-funded students

Countries	NUST	UB	UNZA	Other	Total
Angola	0	1	2	0	**3**
Botswana	0	7	2	0	**9**
Namibia	12	1	0	0	**13**
Zambia	2	0	8	0	**10**
South Africa*	0	0	0	1	**1**
Total	**14**	**9**	**12**	**1**	**36**

* Under staff development, one staff member from CPUT, assisted with PhD studies

Acknowledgements

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Determining the degree of deforestation in the Omusati Region, northern Namibia, with the aid of drone imagery

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Abstract: Deforestation, caused both by clearing of fields and by excessive wood harvesting, has been reported to be widespread in the north-central communal areas in Namibia, yet little quantitative information is available on the severity of this form of land degradation. The two biodiversity observatories Ogongo and Omano go Ndjamba are located in the Omusati Region, taking advantage of the unique situation at the Ogongo Campus of the University of Namibia, where the vegetation is protected in a near-pristine condition. The Omano go Ndjamba observatory is situated about 5 km to the west of this, within the typical communal subsistence agriculture land use system found in the region. High-resolution aerial surveys have been undertaken during March 2017 at both observatories. From the resulting images, normalised excessive green index maps (exG2) have been calculated and individual woody plants were delineated. The woody cover and height of plants could be determined at both observatories using the exG2 index and a DSM generated from the aerial images. Direct deforestation (i.e., the clearing of natural vegetation) occurred on 2.5% of the total area in the Ogongo observatory, and on 13.1% at the Omano go Ndjamba observatory. Forest degradation through wood harvesting, however, is of a far greater concern: whereas the woody cover at Ogongo is on average 43.3%, this has been reduced to between 17.7% and 7.5% (depending on land use) at Omano go Ndjamba. This trend is also associated with a reduction in plant height, with tall shrubs and trees being replaced by short coppicing shrubs at Omano go Ndjamba. The impacts of this forest degradation are a loss of provisioning ecosystem services and the potential for total desertification of the area. The use of UAV (drone) aerial images proved to be very suitable for a quick assessment of degradation states, provided a suitable baseline is available.

Resumo: A desflorestação, tanto pela limpeza dos campos como pela extracção excessiva de madeira, tem uma distribuição ampla nas áreas comuns do Centro-Norte da Namíbia. No entanto, existe pouca informação quantitativa sobre a severidade desta forma de degradação da terra. Os dois observatórios de biodiversidade, Ogongo e Omano go Ndjamba, estão localizados na Região de Omusati, aproveitando-se da situação única no Campus Ogongo da Universidade da Namíbia, onde a vegetação está protegida em estado quase pristino. O observatório Omano go Ndjamba situa-se a cerca de 5Km a Oeste do campus, inserido no sistema de uso da terra comunitátio típico na região, baseado na agricultura de subsistência. Foram realizados levantamentos aéreos de alta resolução durante o mês de Março de 2017, em ambos os observatórios. A partir das imagens resultantes, foram calculados os mapas do Índice Verde Excessivo Normalizado (Normalised Excessive Green Index) (exG2) e delineadas as plantas lenhosas individuais. A cobertura e altura das plantas lenhosas pôde ser determinada em ambos os observatórios com recurso ao uso do índice exG2 e um Modelo Digital de Superfície (DSM) gerado a partir das imagens de satélite. A desflorestação directa (ou seja, a remoção da vegetação natural) ocorreu em 2,5% da área total no observatório de Ogongo, e em 13,1% no observatório de Omano go Ndjamba. No entanto, a degradação florestal devida à extracção de madeira é muito mais preocupante: enquanto que a cobertura lenhosa em Ogongo é, em média, 43,3%, esta foi reduzida para entre 17,7% e 7,5% (dependendo do uso da terra) em Omano go Ndjamba. Isto está também associado a uma redução da altura da planta, com arbustos altos e árvores a serem substituidos por pequenos arbustos de talhadia em Omano go Ndjamba. Os impactos desta degradação florestal são a perda dos serviços de ecossistemas, e o potencial para a total desertificação da área. O uso de imagens aéreas UAV (drone) provou ser bastante adequado para uma rápida avaliação dos estados de degradação, desde que uma referência adequada esteja disponível.

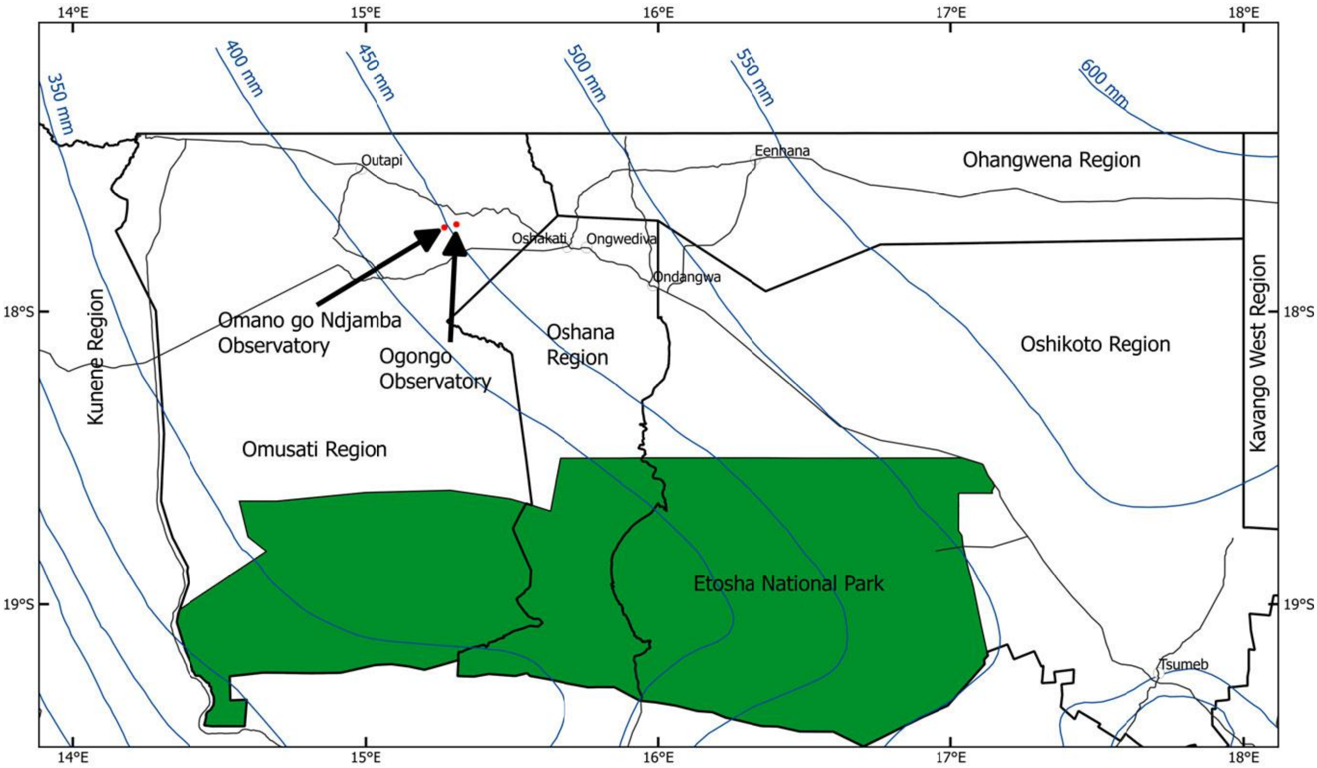

Figure 1: Location of the Ogongo and Omano go Ndjamba biodiversity observatories in northern Namibia. Regional boundaries are indicated in bold black lines, main roads in thin grey lines, and rainfall isohyets in blue lines, with their value along the top edge of the figure.

Introduction

Deforestation is said to be one of the main causes of land degradation and desertification, leading to disrupted ecosystem functioning and a loss of ecosystem services. Hosonuma et al. (2012) make a distinction between deforestation *sensu stricto* as caused by both commercial and subsistence cropping, and forest degradation as caused by timber extraction, logging, firewood collecting, and charcoal production. Both forms (deforestation *sensu stricto* as caused by land clearing as well as forest degradation) are common practices in central northern Namibia, and are commonly referred to as 'deforestation' (Erkkilä, 2001; Klintenberg et al., 2007; Strohbach, 2001). However, little quantitative information on these forms of land degradation is available for Namibia.

Deforestation for cropping is one of the main causes of land degradation in semi-arid regions of the world (Imeson, 2012; Mainguet, 1991; Reynolds et al., 2007). One of the major causes of deforestation in Africa is unsustainable cropping practices (Hosonuma et al., 2012; Mainguet, 1991). Mainguet (1991) specifically mentions a tendency to overcrop (i.e., to clear more land than necessary) to compensate for crop failures resulting from drought and/or poor soils. This holds also true for northern Namibia, where widespread deforestation has been reported (Erkkilä, 2001; Klintenberg et al., 2007; Mendelsohn & el Obeid, 2003; Mendelsohn et al., 2000; Pröpper et al., 2010, 2015).

To study the effects of long-term climate change, a series of permanent biodiversity observation plots were established in 2001 and expanded in 2006. As land use has been identified as a major driver in land degradation, many of these biodiversity observatories have been established in a paired fashion across a land use gradient (Jürgens et al., 2012). Two such biodiversity observatories have been established in the Omusati Region in northern Namibia (Jürgens et al., 2010). The Ogongo observatory is located on the southern part of the Ogongo campus of the University of Namibia. This area is used exclusively for extensive (but fairly light) livestock grazing. In the Cuvelai Delta, no other such (semi) pristine example of Mopane woodlands exists. Roughly 5 km west of this, in the village of Omano go Ndjamba, a second observatory has been established inside a typical communal land use setting. Land uses include cropping, wood and timber harvesting, and livestock grazing. This observatory pair is used as examples to compare the degree of deforestation in the Omusati Region, both as a result of clearing for cropping and from forest degradation caused by timber extraction and general wood harvesting. Using easy-to-obtain high-resolution UAV (drone) aerial photography, we attempt to quantify these land degradation trends in the Omusati Region and compare them to the unique semi-pristine Mopane woodlands at the Ogongo observatory.

Methods

Study area

A regular biodiversity observatory is 1 km^2, or 1,000 by 1,000 m, in size, and is subdivided into one hundred 1 ha units. Hectare numbering is in rows, starting from 0 in the NW corner and ending with 99 in the SE corner (Jürgens et al., 2010, 2012). The position of the observatory is quoted as the northwestern corner.

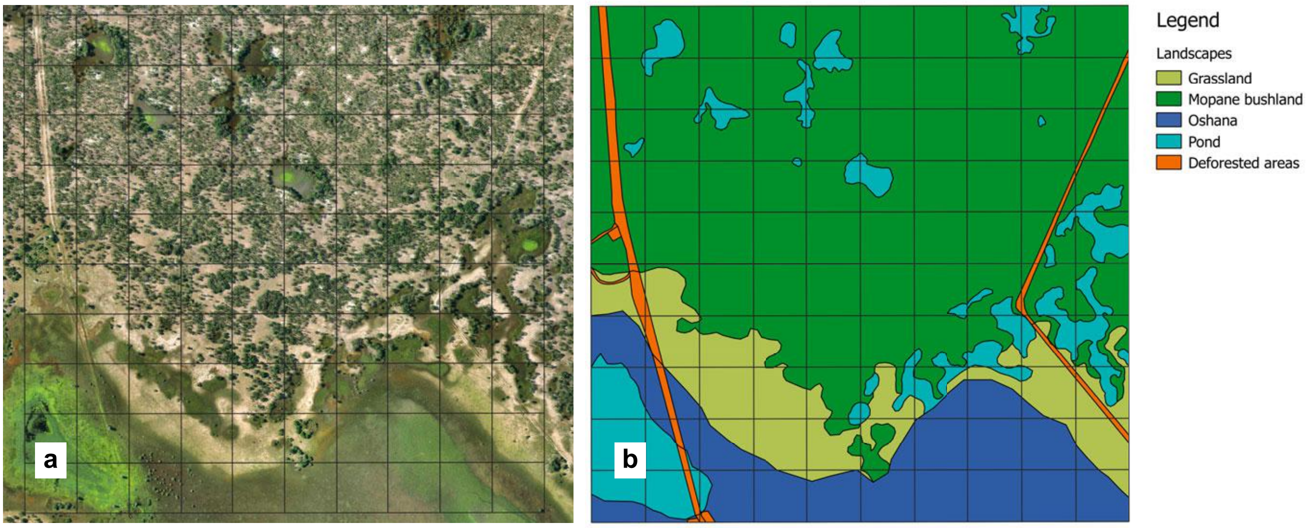

Figure 2: a) aerial image of the Ogongo observatory with observatory hectare grid overlaid; b) map of the landscapes at the observatory with ha grid; c) typical view of the Mopane bushland at the observatory.

The Ogongo observatory is situated at 17.697169˚ S, 15.305209˚ E; the Omano go Ndjamba observatory is at 17.708034˚ S, 15.264797˚ E (Fig. 1).

Both the Ogongo and Omano go Ndjamba observatories are situated in the Mopane savanna *sensu* Giess (1998). The vegetation is dominated by *Colophospermum mopane* shrubs and trees, making it a bushland *sensu* Edwards (1983). A common feature of Mopane-dominated vegetation is the poorly developed herbaceous layer (du Plessis, 2001; Siebert et al., 2003). The Mopane bushlands are interspersed with extensive *iishana* (plural *oshana* — i.e., shallow, broad watercourses of the Cuvelai Delta; Mendelsohn et al., 2013). A full description of the vegetation is presented by Jürgens et al. (2010, pp. 140–163) and Kangombe (2010). The soils are dominated by albic, even glossalbic Solonetz (Jürgens et al., 2010). The brightly bleached topsoil with inherent low herbaceous cover is in stark contrast to the woody vegetation, making discrimination between woody vegetation and the background soil matrix quite feasible.

The topography is almost flat, with a relative altitudinal range at Ogongo of between 1,116.8 and 1,117.7 m above sea level (asl), and at Omano go Ndjamba of between 1,116.8 and 1,119.2 m asl (as derived from the orthophotos, excluding trees, relativized by a possible processing error). The climate is a typical subtropical steppe climate, with roughly 450 to 470 mm mean annual precipitation falling in the summer months between November and April (Jürgens et al., 2010). Full climatic data from the Ogongo weather station are available from the SASSCAL WeatherNet (SASSCAL, 2017; Muche et al., 2018).

Drone survey

An aerial survey of the Ogongo and Omano go Ndjamba observatories was undertaken on 20 March 2017 starting at 16h49 and 17h49, respectively. For the purpose, an eBee (Sensefly) was used with a Canon G9X RGB camera aboard. The weather was clear and sunny, but the sun elevation was fairly low, being shortly before sunset (Ogongo: A_Z 282.4°, β 32.7°; Omano go Ndjamba: A_Z 276.7°, β 18.6°) (A_Z denotes the azimuth angle, β the elevation angle of the sun from the surface) (Cornwall et al., 2017). Pictures were taken from approximately 211 m altitude above ground level, with a planned ground resolution of 5 cm, an individual image footprint of 273.6 m x 182.4 m, and a lateral/longitudinal overlap ratio of 60% by 75%. For Ogongo, 210 individual pictures were taken, whilst for Omano go Ndjamba, 213 pictures were taken. No NIR images could be taken because of equipment failure.

Aerial image analysis and data extraction

The individual images were merged into two separate orthophotos using Pix4Dmapper Pro (Pix4Dmapper Pro, 2016). No ground control points were used. Together with the orthophoto processing, a digital surface model (DSM) and the vegetation indices excessive green (exG), normalised excessive green (exG2), excessive red (exR), and normalised green-red difference (NGRDI) were calculated again using the Pix4Dmapper Pro software (Gitelson et al., 2002; Meyer & Neto, 2008; Rasmussen et al., 2016; Woebbecke et al., 1995).

Based on descriptions of the BIOTA observatories (Jürgens et al., 2010, pp. 140–163), four landscape units were identified on each orthophoto and hand-digitised as a map of these landscapes. In addition, visible land use features were also digitised. These included homesteads, paths, cattle-handling infrastructure ('kraals', etc.), fields, and fenced or unfenced grazing areas. The area of each polygon was determined in QGIS (QGIS 2.14.5-Essen, 2016). Areas in which the natural vegetation has been removed (i.e., fields, homesteads, paths, and other infrastructure) were assumed to be directly deforested, whilst fenced and unfenced (communal) grazing areas were assumed to be either 'pristine' (at Ogongo) or subject to wood harvesting practices.

Table 1: Landscapes and land uses in the Ogongo and Omano go Ndjamba observatories, indicating the area covered and/or destroyed within the observatories.

Landscape	Land use	Area at Ogongo observatory (ha)	Area at Omano go Ndjama observatory (ha)
Grasslands	Total	12.6	3.2
	Grazing	12	2.8
	Paths & infrastructure	0.6	0.4
	Total area destroyed [1]	0.6 (4.9%)	0.4 (12.6%)
Mopane bushland	Total	61.9	73.2
	Grazing	60.5	Fenced grazing: 44.1 Open access grazing: 17.5
	Fields	0	9.1
	Houses	0	0.3
	Paths & infrastructure	1.4	2.2
	Total area deforested	1.4 (2.3%)	11.6 (15.8%)
Iishana	Total	15.6	17.8
	Grazing [2]	15.3	17.4
	Paths & infrastructure	0.3	0.4
	Total area destroyed	0.3 (1.9%)	0.4 (2.2%)
Ponds	Total	10.0	5.8
	Grazing	9.8	5.1
	Fields	0	0.7
	Paths & infrastructure	0.2	Negligible
	Total area deforested	0.2 (1.4%)	0.7 (11.3%)
Total area deforested/destroyed		2.5 (2.5%)	13.1 (13.1%)

[1] By definition, grasslands, including the *iishana*, do not have trees and thus cannot be 'deforested'. Instead, typically through trampling action, the ecosystem functioning is destroyed, generally leading to increased erosion by wind and water.

[2] It is common to see cattle and donkeys wade into the shallow *iishana* in the communal areas to graze (as open-access grazing). This is also apparent from the grass cover of the *iishana* when comparing the two observatories in the aerial photos (Fig. 2 and 3). It is, however, not clear whether ponds are used for this purpose — a slight difference in colouring is apparent, though.

By way of visual inspection, following the method suggested by Meyer and Neto (2008), a threshold value of 0.1 for the exG2 index was determined to be suitable for discriminating the trees from the background grasses at both the Omano go Ndjamba and Ogongo observatories. The normalised excessive green index (exG2) was found to differentiate trees best from the background, given the low sun elevation at the time of image acquisition.

Using the contour extraction utility in QGIS (QGIS 2.14.5-Essen, 2016), lines were drawn around the trees based on this threshold and linked up to form polygons using the fTools plug-in. To facilitate easier processing, the data matrix was reduced as follows:

- All contours other than those of 0.1 threshold were selected and deleted prior to creating polygons.
- Likewise, all contours within landscapes other than the Mopane bushlands were selected and deleted. This selection was extended to include all contours within degraded/deforested areas (e.g., fields, paths, homesteads). The remaining contours were thus only outlines of trees and shrubs standing in grazing areas within the Mopane bushlands.
- After creating polygons, the area of each resulting polygon was calculated. All polygons smaller than 0.01 m^2 (i.e., 10 x 10 cm) were selected and deleted.

The remaining polygons represent trees and shrubs, even juvenile plants. Because of the dense clustering of woody plants at Ogongo, though, it proved difficult to use these 'tree' polygons to measure vegetation cover directly and accurately. Therefore, to determine the difference in woody vegetation cover and structure, systematic sampling points 5 m apart were created across the entire observatory using the Regular Points tool of the fTools plug-in. For each of these 40,401 sampling points, the following values were extracted using the Point Sampling Tool plug-in: the landscape and land use type, the observatory hectare designation, the exG2 value, and the DSM value. These values were exported as a CSV file and imported into Excel for further processing. As the observatories are relatively flat (< 0.5% slope), the DSM value was converted to a vegetation height by deducting the lowest DSM value of a moving window of 20 points across any particular point from the DSM value of that particular point (i.e., the difference in height of any particular point and the lowest altitude within 100 m from that particular point). Thereafter, the dataset was sorted according to landscape and land use, and the sampling points for the Mopane bushland, as used for grazing (light grazing in Ogongo, fenced grazing and open-access grazing at Omano go Ndjamba), extracted. Secondary sorting of the data points was done according to the relative height, and the trees and shrubs grouped into height classes of 0–1 m, 1–2 m, 2–5 m, and higher than 5 m (following Edwards, 1983). Although Edwards (1983) makes a distinction between *single-stemmed* trees and *multi-stemmed* shrubs in the 2–5 m height class, these could not be separated apart based on the aerial photographs and were thus lumped together.

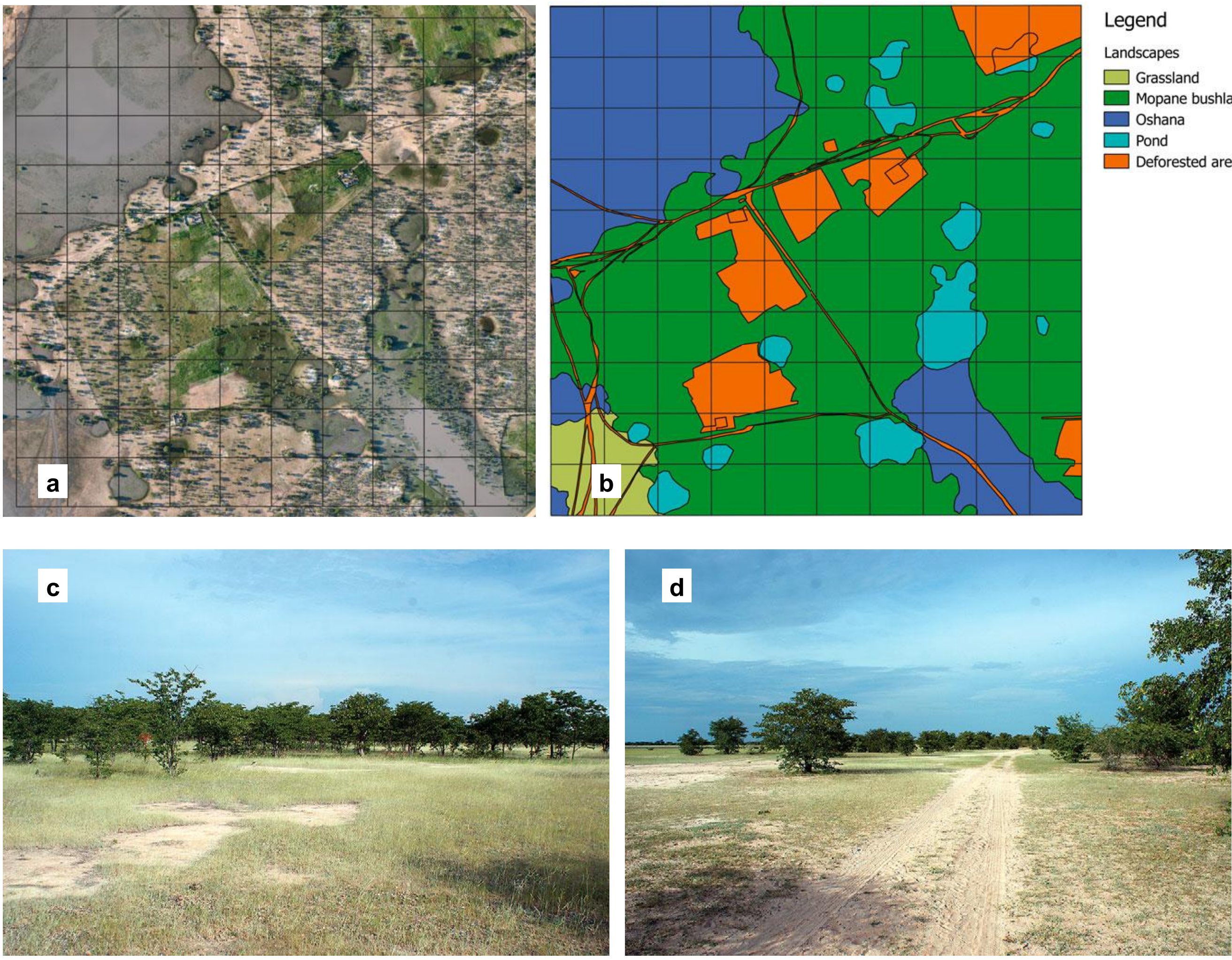

Figure 3: a) aerial image of the Omano go Ndjamba observatory; b) map of the landscapes at the observatory; typical view of the Mopane bushland at the observatory c) fenced and d) open access.

The total number of points in each height class was determined, as was the total number of points (trees, shrubs, and background grass/soil matrix) for the given hectare, landscape, and land use type within each observatory. This frequency distribution (expressed as a percentage of the total number of points) represents the percentage cover for each woody height stratum. For this study, only structural data for the Mopane bushlands were further processed for reporting.

No recent ground data were available for this study. Previously collected data from the observatories date back to 2009 (Jürgens et al., 2010) and can thus be used only as indicative information.

Results

The aerial survey at Ogongo resulted in a GeoTIFF covering 172.38 ha at an average ground sampling distance of 5.13 cm (Fig. 2). Geolocation accuracy (RSM error) is *x* 0.652 m, *y* 0.475 m, and *z* 1.427 m. The aerial survey at Omano go Ndjamba produced a GeoTIFF covering 162.15 ha at an average ground sampling distance of 4.94 cm (Fig. 3). Geolocation accuracy (RSM error) is *x* 0.331 m, *y* 0.324 m, and *z* 0.999 m.

Landscapes and deforestation

The area covered by each landscape and each land use for each observatory is provided in Table 1. A distinction could be made between *iishana*, the associated grasslands on the edge of the *iishana*, ponds, and a matrix of Mopane bushland. Land use features identified included roads and paths, cattle-handling infrastructure ('kraals'), fields, and homesteads (grouped as 'deforested areas'). The remaining area was classed as grazing areas. At Omano go Ndjamba, a differentiation could be made between fenced and open-access grazing areas (Tab. 1).

Woody cover and structure

The contour extraction of the woody plants based on the exG2 index at Ogongo is illustrated in Figure 4, and in Figure 5 for Omano go Ndjamba. The difference in tree and shrub cover between the two land use systems is clearly visible in these images.

Woody cover on Ogongo, as determined by point sampling, was 43.3% (n = 24,048, sd = 14.0%). At Omano go Ndjamba, the woody cover is reduced to 17.7% (n = 16,473, sd = 14.6%) within fenced grazing areas, and to as little as 7.5% (n = 6,630, sd = 5.5%) within the open-access areas. The differences in woody vegetation cover of the two observatories and three land use types are depicted in Figure 6.

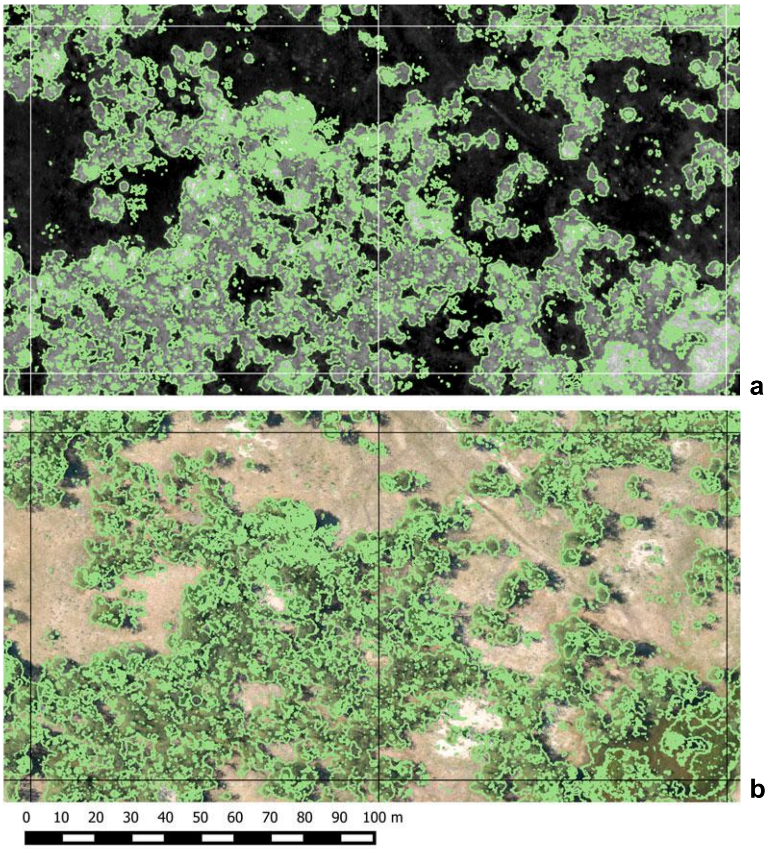

Figure 4: a) exG2 index image of Ogongo hectares 55 and 56; b) RGB image of the same hectares. On both, the contours extracted from the exG2 image to delineate trees and shrubs are superimposed.

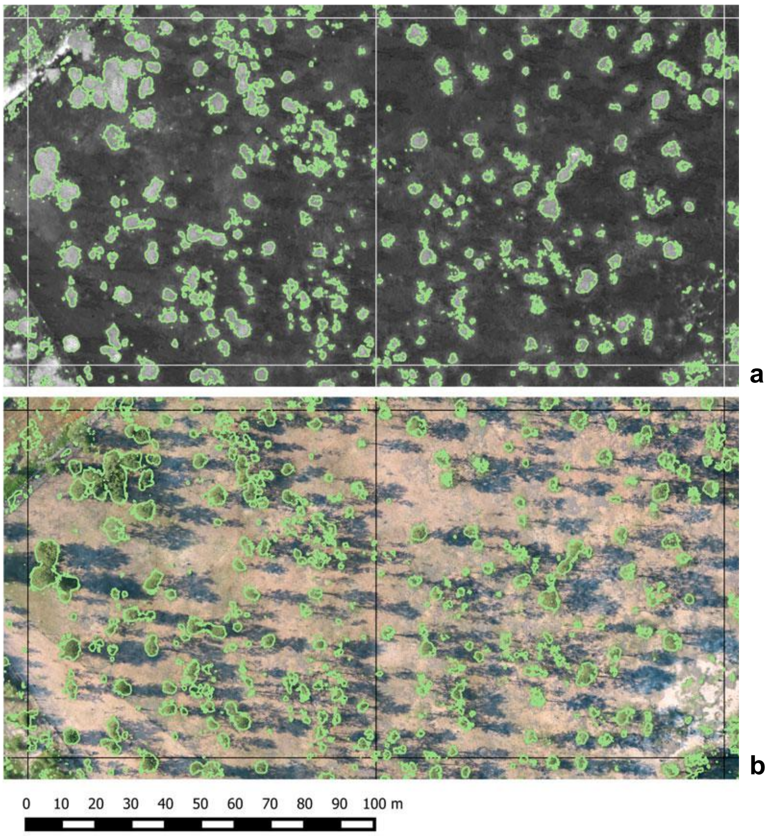

Figure 5: a) exG2 index image of Omano go Ndjamba hectares 55 and 56; b) RGB image of the same hectares. On both, the contours extracted from the exG2 image to delineate trees and shrubs are superimposed. Note the stark difference in tree cover compared to Ogongo in Figure 4.

Discussion

Direct deforestation is remarkably low at Omano go Ndjamba, with only 13.1% of the total area of the Omano go Ndjamba observatory cleared for various purposes. Yet at least half of the cleared fields seem uncultivated, overgrown with weeds. The reason for this fallowing is not known. Soils in the north-central regions are known to be of low fertility and subject to further degradation through erosion and leaching (Mendelsohn et al., 2000; Rigourd & Sappe, 1999). This could be the cause of fallowing, as is happening extensively in the Kavango Region to the east of the present study area (Pröpper et al., 2010, 2015). This trend strongly suggests overcultivation as defined by Mainguet (1991).

Little recognised as a cause of degradation is the excessive number of paths seen at both observatories. Where Ogongo has only two paths crossing the observatory, these are associated with a wide cut line, covering in total 2.6 ha (Fig. 2, Tab. 1). At the Omano go Ndjamba village, paths are generally limited to single-track vehicle tracks, but often with multiple tracks next to one another. These tracks cover 3 ha (Fig. 3, Tab. 1). It is often observed in these communal areas that as tracks deteriorate, new tracks are formed adjacent to the previous track. 'Shortcuts' to 'new destinations' also lead to excessive tracks in these areas (own observation). These tracks not only destroy the biota on the soil surface but also cause damage to the subsoil layers by compaction and reduced soil moisture availability, and are a potential cause of erosion (Webb & Wilshire, 1983).

Of far greater concern is the forest degradation resulting from wood harvesting, as depicted in Figure 6. Mopane wood is widely used for construction and firewood. For fencing, both posts are cut and young branches are used for cladding the fence (Mendelsohn et al., 2013; own observations). This high use of timber for construction and fencing is very evident in the difference in the 2–5 m height class between the two observatories. The strong coppicing ability of Mopane allows it to survive quite a while after being harvested (Mlambo & Mapaure,

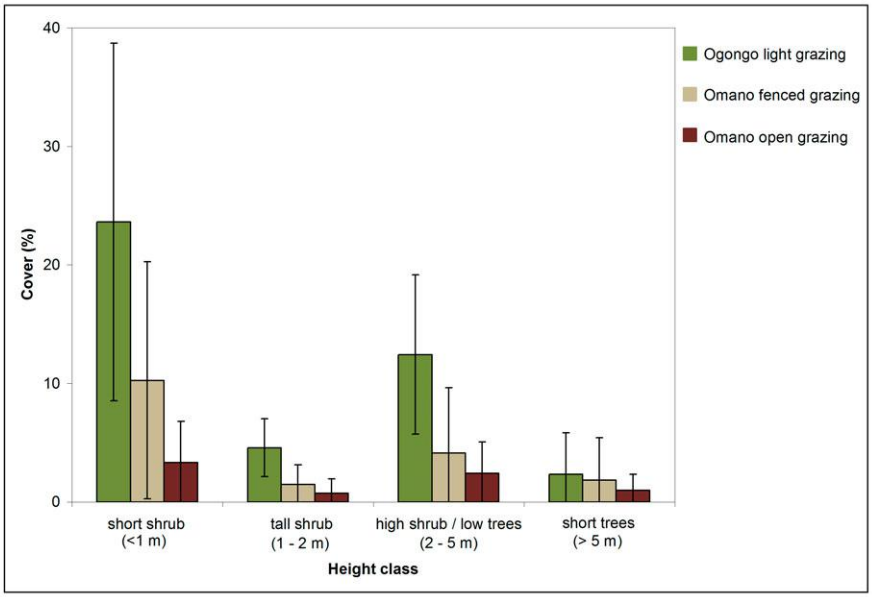

Figure 6: Woody plant density illustrating the vegetation structure of the Mopane bushlands at Ogongo (light grazing) and Omano go Ndjamba (fenced grazing and open-access grazing). Error bars indicate the standard deviation.

2006; Scholes, 1990; Strohbach, 2000). The high cover of short shrubs on Omano go Ndjamba is likely a result of coppicing Mopane shrubs. The reason for the high cover of this size class at Ogongo is not clear — it could be seedlings and/or juvenile plants as a first stage to very dense bush encroachment. Mopane, however, does not survive repeated harvesting and intense browsing for an extended period of time, resulting in the very low cover of this species in the open-access grazing areas at Omano go Ndjamba. This overutilisation eventually leads to desertification in the most severe form.

Conclusion

High-resolution aerial photography proved to be a valuable tool in assessing the current condition of the vegetation. Because of the high resolution of the imagery, identification of individual trees and shrubs is easy. Similar trends have been described by Jürgens et al. (2010). Unfortunately, the available data are outdated concerning the rapidly changing environment through intensive land use and seasonal climatic variations.

Ground truth data are therefore not crucial for determining the density of woody plants but will help with species identification (Oldeland et al., 2017) and thus with improved interpretation of the aerial imagery. This is more important if studying species dynamics as a result of various forms of land use and/or land degradation. The use of drones allows for regular repetition (ad lib) of such an aerial survey at a fraction of the cost of conventional aerial surveys. Added advantages are the high resolution of these images, allowing for the easy recognition of features and the possibility of developing a three-dimensional image through stereoscopic effects (see Knox et al., 2018). Drawbacks are the relatively small area that can be surveyed at once with this technology (compared to the large areas covered by regular aerial photography or even satellite-based remote sensing), and the difficulty in exact geolocation of the imagery without the use of accurate ground control points and/or differential GPS technology. Nevertheless, this manner of monitoring the degree of deforestation on selected sample sites is quite feasible in future.

Experimentation with the most suitable season for such a survey should be done to be able to best discriminate between woody plants and the background soil/grass matrix. An aerial survey during spring, after leaf flush by the woody species but before the onset of the rainy season, might be ideal here and for other observatories throughout Namibia.

Direct deforestation for cropping still seems to be within reasonable limits, judging by the example of the Omano go Ndjamba observatory. Of far bigger concern is the indirect deforestation caused by the extensive harvesting of timber and nontimber products. At this stage, roughly two-thirds of the woody vegetation has been lost. This indirect deforestation is a good indication of the cause of the commonly observed vegetation cover difference along the Namibian-Angolan border (Marsh & Seely, 1992; Mendelsohn et al., 2000, 2013). In turn, this is likely resulting in a severe reduction in ecosystem functioning and thus in ecosystem service delivery. One obvious result will be the reduction in wood availability (both wood for construction and firewood) to the subsistence farmers. Less well understood, but likely of equal importance, is the effect that deforestation has on soil protection and soil fertility, especially considering that *Colophospermum mopane*, as a leguminose woody plant, is known to enrich soils with plant-available nitrogen (Mlambo et al., 2007).

It needs to be considered that the Omano go Ndjamba observatory is only a single, small sample within the larger Mopane savanna in the north-central regions of Namibia. Conversely, Ogongo is a uniquely conserved location, and similar conserved areas are unlikely to be found in the Omusati Region.

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References

Cornwall, C., Horiuchi, A. & Lehman, C. (2017) NOAA solar position calculator. https://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html

Edwards, D. (1983) A broad-scale structural classification of vegetation for practical purposes. *Bothalia*, **14**, 705–712.

Erkkilä, A. (2001) *Living on the land: change in forest cover in north-central Namibia, 1943–1996.* Faculty of Forestry, University of Joensuu, Joensuu, Finland.

Giess, W. (1998) A preliminary vegetation map of Namibia. *Dinteria*, **4**, 1–112.

Gitelson, A.A., Kaufman, Y.J., Stark, R. & Rundquist, D. (2002) Novel algorithms for remote estimation of vegetation fraction. *Remote Sensing of Environment*, **80**, 76–87.

Hosonuma, N., Herold, M., De Sy, V., De Fries, R.S., Brockhaus, M., Verchot, L., Angelsen, A. & Romijn, E. (2012) An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters*, **7**, 044009.

Imeson, A.C. (2012) *Desertification, land degradation and sustainability.* Wiley-Blackwell, Chichester.

Jürgens, N., Haarmeyer, D.H., Luther-Mosebach, J., Dengler, J., Finckh, M. & Schmiedel, U. (eds.) (2010) *Patterns at local scale: the BIOTA Observatories.* Klaus Hess Publishers, Göttingen & Windhoek.

Jürgens, N., Schmiedel, U., Haarmeyer, D.H., et al. (2012) The BIOTA Biodiversity Observatories in Africa — a standardized framework for large-scale environmental monitoring. *Environmental Monitoring and Assessment*, **184**, 655–678.

Kangombe, F.N. (2010) The vegetation of Omusati and Oshana regions, central-northern Namibia. M.Sc. thesis, University of Pretoria, Pretoria.

Klintenberg, P., Seely, M. & Christiansson, C. (2007) Local and national perceptions of environmental change in central northern Namibia: Do they correspond? *Journal of Arid Environments*, **69**, 506–525.

Knox, N., Strohbach, B. & De Cauwer, V. (2018) Potential use of 3D derived products generated from unmanned aerial vehicle (UAV) imagery for monitoring forest degradation and woodland structure changes in the Namibian dry woodlands. This volume.

Mainguet, M. (1991) *Desertification — natural background and human mismanagement.* Springer, Berlin.

Marsh, A. & Seely, M. (eds.) (1992) *Oshanas: Sustaining people, environment and development in central Owambo, Namibia.* Desert Research Foundation of Namibia, Windhoek.

Mendelsohn, J. & el Obeid, S. (2003) *Sand and Water. A profile of the Kavango Region.* Struik Publishers & RAISON, Cape Town & Windhoek.

Mendelsohn, J., el Obeid, S. & Roberts, C. (2000) *A profile of north-central Namibia*. Gamsberg Macmillan Publishers for the Directorate of Environmental Affairs, Namibia.

Mendelsohn, J., Jarvis, A. & Robertson, T. (2013) *A profile and Atlas of the Cuvelai-Etosha Basin*. RAISON and Gondwana Collection, Windhoek, Namibia.

Meyer, G.E. & Neto, J.C. (2008) Verification of color vegetation indices for automated crop imaging applications. *Computers and Electronics in Agriculture*, **63**, 282–293.

Mlambo, D. & Mapaure, I. (2006) Post-fire resprouting of *Colophospermum mopane* saplings in a southern African savanna. *Journal of Tropical Ecology*, **22**, 231–234.

Mlambo, D., Mwenje, E. & Nyathi, P. (2007) Effects of tree cover and season on soil nitrogen dynamics and microbial biomass in an African savanna woodland dominated by *Colophospermum mopane*. *Journal of Tropical Ecology*, **23**, 437–448.

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: present state, challenges, and achievements of the regional climatic observation network and database. This volume.

Oldeland, J., Große-Stoltenberg, A., Naftal, L. & Strohbach, B.J. (2017) The potential of UAV derived image features for discriminating savannah tree species. *The roles of remote sensing in nature conservation* (ed. by R. Díaz-Delgado, R. Lucas, and C. Hurford), pp. 183–201. Springer International Publishing, Berlin.

Pix4Dmapper Pro (2016) Pix4D SA, Lausanne, Switzerland.

du Plessis, F. (2001) A phytosociological synthesis of Mopaneveld. M.Sc. thesis, University of Pretoria, Pretoria.

Pröpper, M., Gröngröft, A., Falk, T. et al. (2010) Causes and perspectives of land-cover change through expanding cultivation in Kavango. *Implications for landuse and management Biodiversity in southern Africa* (ed. by M.T. Hoffman, U. Schmiedel, and N. Jürgens), pp. 2–30. Klaus Hess Publishers, Göttingen & Windhoek.

Pröpper, M., Gröngröft, A., Finckh, M., Stirn, S., De Cauwer, V., Lages, F., Masamba, W., Murray-Hudson, M.A., Schmidt, L., Strohbach, B. & Jürgens, N. (eds.) (2015) *The Future Okavango. Findings, Scenarios and Recommendations for Action*. University of Hamburg, Hamburg & Windhoek.

QGIS 2.14.5-Essen (2016) Open Source Geospatial Foundation (OSGeo).

Rasmussen, J., Ntakos, G., Nielsen, J., Svensgaard, J., Poulsen, R.N. & Christensen, S. (2016) Are vegetation indices derived from consumer-grade cameras mounted on UAVs sufficiently reliable for assessing experimental plots? *European Journal of Agronomy*, **74**, 75–92.

Reynolds, J.F., Maestre, F.T., Kemp, P.R., Stafford-Smith, D.M. & Lambin, E. (2007) Natural and human dimensions of land degradation in drylands: causes and consequences. *Terrestrial ecosystems in a changing world* (ed. by J.G. Canadell, D.E. Pataki, and L.F. Pitelka), pp. 247–257. Springer, Berlin.

Rigourd, C. & Sappe, T. (1999) Investigating into soil fertility in the North Central regions. *Conservation tillage with animal traction* (ed. by P.G. Kaumbutho and T.E. Simalenga). Animal Traction Network for Eastern and Southern Africa (ATNESA), Harare.

SASSCAL (2017) SASSCAL WeatherNet – http://www.sasscalweathernet.org/weatherstat_infosheet_we.php?loggerid_crit=31212.

Scholes, R.J. (1990) The regrowth of *Colophospermum mopane* following clearing. *Journal of the Grassland Society of Southern Africa*, **7**, 147–151.

Siebert, F., Bredenkamp, G.J. & Siebert, S.J. (2003) A comparison of Mopaneveld vegetation in South Africa, Namibia and Zimbabwe. *Bothalia*, **33**, 121–134.

Strohbach, B.J. (2000) Vegetation degradation trends in the northern Oshikoto region: II. The *Colophospermum mopane* shrublands. *Dinteria*, **26**, 63–75.

Strohbach, B.J. (2001) Vegetation degradation in Namibia. *Journal of the Namibia Scientific Society*, **49**, 127–156.

Webb, R.H. & Wilshire, H.G. (eds.) (1983) *Environmental effects of off-road vehicles: impacts and management in arid regions.* Springer New York, New York.

Woebbecke, D.M., Meyer, G.E., Von Bargen, K. & Mortensen, D.A. (1995) Color indices for weed identification under various soil, residue, and lighting conditions. *Transactions of the ASAE*, **38**, 259–269.

References [CrossRef]

Cornwall, C., Horiuchi, A. & Lehman, C. (2017) NOAA solar position calculator. https://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html

Edwards, D. (1983) A broad-scale structural classification of vegetation for practical purposes. *Bothalia*, **14**, 705–712. CrossRef

Erkkilä, A. (2001) *Living on the land: change in forest cover in north-central Namibia, 1943–1996*. Faculty of Forestry, University of Joensuu, Joensuu, Finland.

Giess, W. (1998) A preliminary vegetation map of Namibia. *Dinteria*, **4**, 1–112.

Gitelson, A.A., Kaufman, Y.J., Stark, R. & Rundquist, D. (2002) Novel algorithms for remote estimation of vegetation fraction. *Remote Sensing of Environment*, **80**, 76–87. CrossRef

Hosonuma, N., Herold, M., De Sy, V., De Fries, R.S., Brockhaus, M., Verchot, L., Angelsen, A. & Romijn, E. (2012) An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters*, **7**, 044009. CrossRef

Imeson, A.C. (2012) *Desertification, land degradation and sustainability*. Wiley-Blackwell, Chichester.

Jürgens, N., Haarmeyer, D.H., Luther-Mosebach, J., Dengler, J., Finckh, M. & Schmiedel, U. (eds.) (2010) *Patterns at local scale: the BIOTA Observatories.* Klaus Hess Publishers, Göttingen & Windhoek.

Jürgens, N., Schmiedel, U., Haarmeyer, D.H., et al. (2012) The BIOTA Biodiversity Observatories in Africa — a standardized framework for large-scale environmental monitoring. *Environmental Monitoring and Assessment*, **184**, 655–678. CrossRef

Kangombe, F.N. (2010) The vegetation of Omusati and Oshana regions, central-northern Namibia. M.Sc. thesis, University of Pretoria, Pretoria.

Klintenberg, P., Seely, M. & Christiansson, C. (2007) Local and national perceptions of environmental change in central northern Namibia: Do they correspond? *Journal of Arid Environments*, **69**, 506–525. CrossRef

Knox, N., Strohbach, B. & De Cauwer, V. (2018) Potential use of 3D derived products generated from unmanned aerial vehicle (UAV) imagery for monitoring forest degradation and woodland structure changes in the Namibian dry woodlands. This volume. CrossRef

Mainguet, M. (1991) *Desertification — natural background and human mismanagement.* Springer, Berlin.

Marsh, A. & Seely, M. (eds.) (1992) *Oshanas: Sustaining people, environment and development in central Owambo, Namibia.* Desert Research Foundation of Namibia, Windhoek.

Mendelsohn, J. & el Obeid, S. (2003) *Sand and Water. A profile of the Kavango Region.* Struik Publishers & RAISON, Cape Town & Windhoek.

Mendelsohn, J., el Obeid, S. & Roberts, C. (2000) *A profile of north-central Namibia*. Gamsberg Macmillan Publishers for the Directorate of Environmental Affairs, Namibia.

Mendelsohn, J., Jarvis, A. & Robertson, T. (2013) *A profile and Atlas of the Cuvelai-Etosha Basin*. RAISON and Gondwana Collection, Windhoek, Namibia.

Meyer, G.E. & Neto, J.C. (2008) Verification of color vegetation indices for automated crop imaging applications. *Computers and Electronics in Agriculture*, **63**, 282–293. CrossRef

Mlambo, D. & Mapaure, I. (2006) Post-fire resprouting of *Colophospermum mopane* saplings in a southern African savanna. *Journal of Tropical Ecology*, **22**, 231–234. CrossRef

Mlambo, D., Mwenje, E. & Nyathi, P. (2007) Effects of tree cover and season on soil nitrogen dynamics and microbial biomass in an African savanna woodland dominated by *Colophospermum mopane*. *Journal of Tropical Ecology*, **23**, 437–448. CrossRef

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: history, state of Measuring Network, database and online presentation, challenges & success. This volume. CrossRef

Oldeland, J., Große-Stoltenberg, A., Naftal, L. & Strohbach, B.J. (2017) The potential of UAV derived image features for discriminating savannah tree species. *The roles of remote sensing in nature conservation* (ed. by R. Díaz-Delgado, R. Lucas, and C. Hurford), pp. 183–201. Springer International Publishing, Berlin. CrossRef

Pix4Dmapper Pro (2016) Pix4D SA, Lausanne, Switzerland.

du Plessis, F. (2001) A phytosociological synthesis of Mopaneveld. M.Sc. thesis, University of Pretoria, Pretoria.

Pröpper, M., Gröngröft, A., Falk, T. et al. (2010) Causes and perspectives of land-cover change through expanding cultivation in Kavango. *Implications for landuse and management Biodiversity in southern Africa* (ed. by M.T. Hoffman, U. Schmiedel, and N. Jürgens), pp. 2–30. Klaus Hess Publishers, Göttingen & Windhoek.

Pröpper, M., Gröngröft, A., Finckh, M., Stirn, S., De Cauwer, V., Lages, F., Masamba, W., Murray-Hudson, M.A., Schmidt, L., Strohbach, B. & Jürgens, N. (eds.) (2015) *The Future Okavango. Findings, Scenarios and Recommendations for Action*. University of Hamburg, Hamburg & Windhoek.

QGIS 2.14.5-Essen (2016) Open Source Geospatial Foundation (OSGeo).

Rasmussen, J., Ntakos, G., Nielsen, J., Svensgaard, J., Poulsen, R.N. & Christensen, S. (2016) Are vegetation indices derived from consumer-grade cameras mounted on UAVs sufficiently reliable for assessing experimental plots? *European Journal of Agronomy*, **74**, 75–92. CrossRef

Reynolds, J.F., Maestre, F.T., Kemp, P.R., Stafford-Smith, D.M. & Lambin, E. (2007) Natural and human dimensions of land degradation in drylands: causes and consequences. *Terrestrial ecosystems in a changing world* (ed. by J.G. Canadell, D.E. Pataki, and L.F. Pitelka), pp. 247–257. Springer, Berlin.

Rigourd, C. & Sappe, T. (1999) Investigating into soil fertility in the North Central regions. *Conservation tillage with animal traction* (ed. by P.G. Kaumbutho and T.E. Simalenga). Animal Traction Network for Eastern and Southern Africa (ATNESA), Harare.

SASSCAL (2017) SASSCAL WeatherNet — Welcome to the weather stations of Angola, Botswana, Namibia and Zambia. http://www.sasscalweathernet.org/weatherstat_infosheet_we.php?loggerid_crit=31212.

Scholes, R.J. (1990) The regrowth of *Colophospermum mopane* following clearing. *Journal of the Grassland Society of Southern Africa*, **7**, 147–151. CrossRef

Siebert, F., Bredenkamp, G.J. & Siebert, S.J. (2003) A comparison of Mopaneveld vegetation in South Africa, Namibia and Zimbabwe. *Bothalia*, **33**, 121–134. CrossRef

Strohbach, B.J. (2000) Vegetation degradation trends in the northern Oshikoto region: II. The *Colophospermum mopane* shrublands. *Dinteria*, **26**, 63–75.

Strohbach, B.J. (2001) Vegetation degradation in Namibia. *Journal of the Namibia Scientific Society*, **49**, 127–156.

Webb, R.H. & Wilshire, H.G. (eds.) (1983) *Environmental effects of off-road vehicles: impacts and management in arid regions.* Springer New York, New York. CrossRef

Woebbecke, D.M., Meyer, G.E., Von Bargen, K. & Mortensen, D.A. (1995) Color indices for weed identification under various soil, residue, and lighting conditions. *Transactions of the ASAE*, **38**, 259–269. CrossRef

Potential use of 3D-derived products generated from unmanned aerial vehicle (UAV) imagery for monitoring forest degradation and woodland structure changes in the Namibian dry woodlands

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Introduction

Woodlands in the SASSCAL region are variable in terms of species composition, density, and structure. Though many of the species are valued for their timber, management and effective monitoring of these woodlands pose several challenges, such as inaccessibility and limited funding for agencies to regularly monitor the woodlands (De Cauwer et al., 2018).

Different remote sensing approaches (in terms of data and analysis) have been demonstrated to be efficient mechanisms for monitoring changes in woodland cover. The use of optical remote sensing in monitoring dry woodlands has proved challenging and resulted in underestimating the cover and distribution of open woodlands (Bastin et al., 2017). With the use of an integrated LiDAR and SAR approach, Mathieu et al. (2018) have demonstrated an effective means to assessing the distribution and fractional woody cover of savanna forests (including the dry woodlands of Namibia). For regional scales, this method is likely to pave the way for future monitoring of dry woodlands. Such regional-scale monitoring, however, will not enable forest managers to capture and monitor localised changes that occur in the dry woodlands as a result of forest degradation caused by extraction of timber for construction and carving, firewood collection, etc. Strohbach (2018) has been able, with the use of UAV technology, in particular by combining a UAV-derived digital surface model (DSM) and RGB imagery, to compare the degree of deforestation and forest degradation, at a small scale, in the Omusati region (Fig. 4-6 in Strohbach, 2018). Here we wish to present an approach for analysing UAV-derived 3D products, generated during processing, to quantify structural properties of woodlands, which could then be used to monitor small-scale forest degradation.

Methods

Using the same flight planning parameters outlined by Strohbach (2018), imagery was acquired on March 21, 2017 (between 13h37 and 14h29) taken over the paired SASSCAL long-term observatories of Mile 46 and Mutompo (Jürgens et al., 2010), located in the dry woodlands of the northern Kalahari. Mutompo is a communal grazing land, and Mile 46 is a site located at the Alex Muranda Livestock Development Centre. A total of 411 images, with a spatial resolution of 5 cm (resampled to 25 cm to facilitate faster processing), were acquired over an area of approximately 325 ha covering these two sites.

Basic pre-processing outlined in Strohbach (2018) was done with Pix4DMapper Pro (Pix4D, Lausanne, Switzerland). From this pre-processing, a mosaicked RGB image and an *x, y, z* point cloud dataset were obtained (RMSE error (m): $x = 0.14$, $y = 0.19$, $z = 0.47$). To enable the generation of this point cloud data set for 3D modelling, sufficient overlap (long track 60–85%, across track 30–70% [Pix4D, 2018]) between the different images is needed. In this case there were more than five overlapping images covering each location within the study area (60% by 75% across/long track overlap). Using the ENVI-LIDAR tool in ENvironment for Visualizing Images (ENVI) software version 5.4 *(Exelis Visual Information Solutions, Boulder, Colorado)*, both a digital elevation model (DEM) and digital surface model (DSM) were generated from the point cloud data. Based on the difference between the DEM and the DSM, one can calculate the heights of individual trees (Fig. 1), assess woody

Table 1: The structural breakdown of woody cover in the two management units at Mile 46 and Mutompo derived from analysis of derived point cloud tree height classifications.

Cover	Mile 46 – ha (%)	Mutompo – ha (%)	Total – ha (%)
Non-woody	120 (84.8)	112 (86.1)	233 (85.4)
Shrub (1–1.5 m)	7 (5.0)	5 (3.5)	12 (4.3)
Tree (1.5–5 m)	11 (7.8)	9 (7.2)	20 (7.5)
Tree (5–10 m)	3 (2.3)	4 (2.8)	7 (2.5)
Tree (> 10 m)	0.3 (0.2)	0.5 (0.4)	0.8 (0.3)

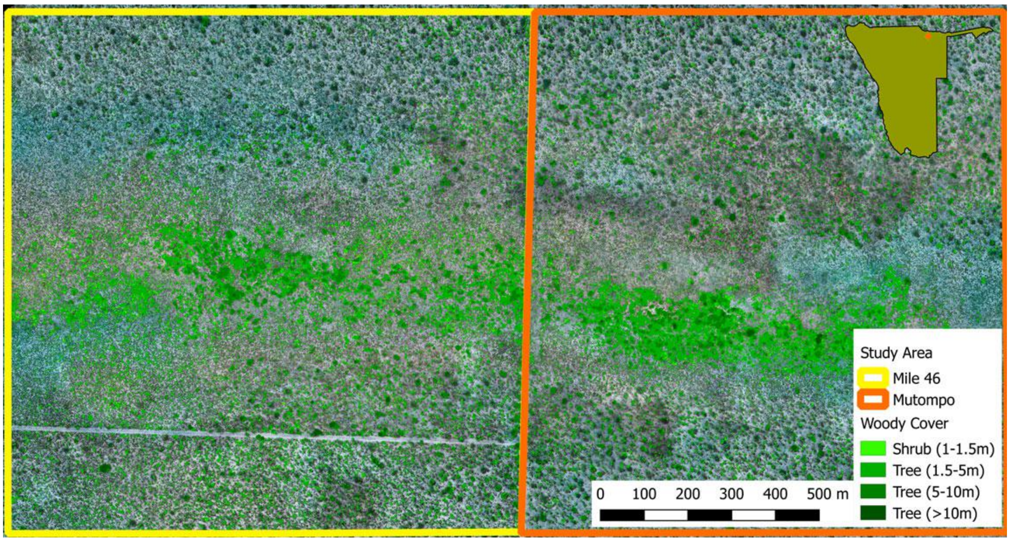

Figure 1: Woody cover height classification derived from processing of UAV imagery point clouds

cover (Tab. 1), determine woody cover per height class (Tab. 1), and generate 3D transects (Fig. 2).

3D Product Outputs

The interpretation of Figure 1 and Table 1 would provide similar outputs to those generated by Strohbach (2018), but with the additional accuracy provided by combining the DEM and DSM in the modelling process. The 3D modelling has the advantage of enabling the analysis of small-scale changes in woody vegetation structure, as shown in the 3D image transect examples (Fig. 2). The image transect analysis could either be done based purely on the height classification (Fig. 2a,c) or combine both the height information and the spectral information (Fig. 2b,d). Oldeland et al. (2017) have recently demonstrated the feasibility of identifying abundant species in Namibian savanna woodlands based on RGB UAV imagery. Combining a woody species map with structural information derived from 3D modelling could thus provide a means to studying the variation in structure of the canopy understory (Fig. 2c,d). Such an analysis would be a valuable contribution to forest management monitoring of selective harvesting of canopies, but this technique still has to be explored to determine its potential applicability in an operational setting (i.e., cost versus value, potential to upscale, skills and requirements).

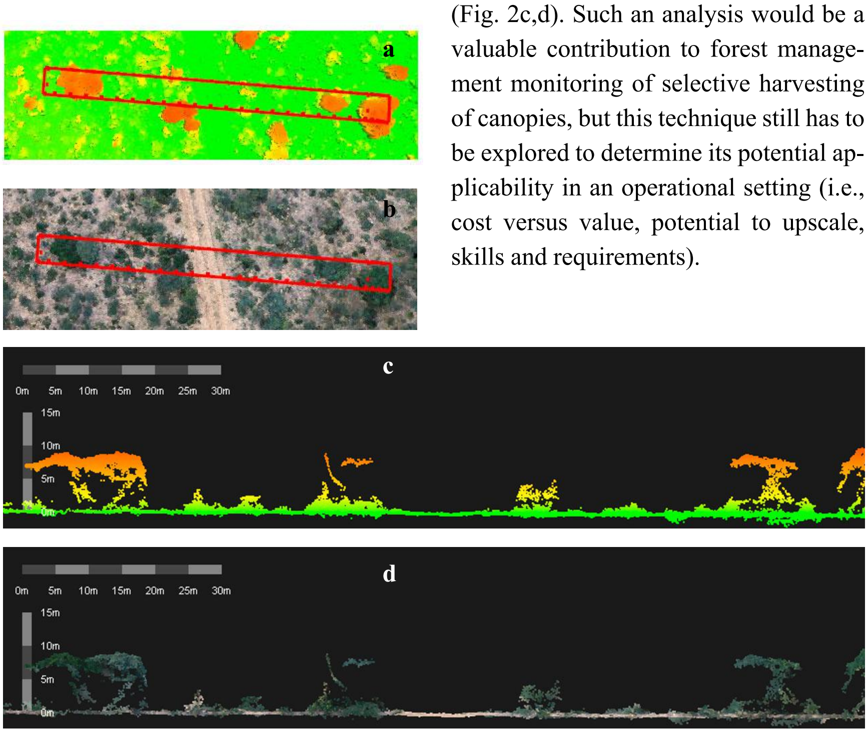

Figure 2: 3D transect analysis of dry woodlands, based on (a) and (c) height-scaled transect and (b) and (d) true-colour imagery (RGB) transect (the transect profile has been stretched to aid interpretation).

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References

Bastin, J.F., Berrahmouni, N., Grainger, A. et al. (2017) The extent of forest in dryland biomes. *Science*, **356(6338)**, 635–638.

De Cauwer, V., Knox, N., Kobue-Lekalake, R., Lepetu, J.P., Matenanga, O., Naidoo, S., Nott, A., Parduhn, D., Sichone, P., Tshwenyane, S., Yeboah, E. & Revermann, R. (2018) Woodland resources and management in southern Africa. This volume.

Jürgens, N., Haarmeyer, D.H., Luther-Mosbach, J., Dengler, J., Finckh, M. & Schmiedel, U. (eds.) (2010) *Biodiversity in Southern Africa **1**: Patterns at local scale — the BIOTA Observatories*. Klaus Hess Publishers, Göttingen & Windhoek.

Mathieu, R., Wessels, K., Main, R., Naidoo, L., van der Bergh, F. & Erasmus, B. (2018) A radar- and LiDAR-based earth observation system for monitoring savannah woody structure in southern Africa. This volume.

Oldeland, J., Große-Stoltenberg, A., Naftal, L. & Strohbach, B.J. (2017) The potential of UAV-derived image features for discriminating savannah tree species. *The roles of remote sensing in nature conservation* (ed. by R. Díaz-Delgado, R. Lucas, & C. Hurford), pp. 183–201. Springer, Cham.

Pix4D. 2018. Designing the image acquisition plan. https://support.pix4d.com/hc/en-us/articles/202557409#gsc.tab=0 (Access Date: Jan 2018)

Strohbach, B. (2018) Determining the degree of deforestation in the Omusati Region, northern Namibia, with the aid of drone imagery. This volume.

References [CrossRef]

Bastin, J.F., Berrahmouni, N., Grainger, A. et al. (2017) The extent of forest in dryland biomes. *Science*, **356(6338)**, 635–638. CrossRef

De Cauwer, V., Knox, N., Kobue-Lekalake, R., Lepetu, J.P., Matenanga, O., Naidoo, S., Nott, A., Parduhn, D., Sichone, P., Tshwenyane, S., Yeboah, E. & Revermann, R. (2018) Woodland resources and management in southern Africa. This volume. CrossRef

Jürgens, N., Haarmeyer, D.H., Luther-Mosbach, J., Dengler, J., Finkh, M. & Schmiedel, U. (eds.) (2010) *Biodiversity in Southern Africa **1**: Patterns at local scale — the BIOTA Observatories*. Klaus Hess Publishers, Göttingen & Windhoek.

Mathieu, R., Wessels, K., Main, R., Naidoo, L., van der Bergh, F. & Erasmus, B. (2018) A radar- and LiDAR-based earth observation system for monitoring savannah woody structure in southern Africa. This volume. CrossRef

Oldeland, J., Große-Stoltenberg, A., Naftal, L. & Strohbach, B.J. (2017) The potential of UAV-derived image features for discriminating savannah tree species. *The roles of remote sensing in nature conservation* (ed. by R. Díaz-Delgado, R. Lucas, & C. Hurford), pp. 183–201. Springer, Cham. CrossRef

Pix4D. 2018. Designing the image acquisition plan. https://support.pix4d.com/hc/en-us/articles/202557409#gsc.tab=0 (Access Date: Jan 2018)

Strohbach, B. (2018) Determining the degree of deforestation in the Omusati Region, northern Namibia, with the aid of drone imagery. This volume. CrossRef

Biodiversity

Biodiversity observation – an overview of the current state and first results of biodiversity monitoring studies

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Abstract: The SASSCAL region is home to a very rich biodiversity, which provides significant economic and intrinsic value to human society. This biodiversity, however, is subject to multiple stresses emerging from human land use and climate change, which leads to biodiversity loss at substantial scale. To assess the current state and changes in biodiversity in the SASSCAL region, a standardised biodiversity observation network has been established. The network comprises 47 biodiversity observatories and 10 auxiliary observatories, where biodiversity change is monitored according to a standardised approach. The network currently covers the countries of Angola, Namibia, Zambia, and South Africa.

The newly established observatories in Angola and Zambia provided urgently needed baseline inventory data on flora and faunal species for the study areas. The observatories in Namibia and South Africa already extend up to 17 or even 30 years and provide important insights into the complexity of the biodiverse systems and their drivers.

We provide an overview of the outcomes of the biodiversity assessment and monitoring work at the observatories. We discuss the contribution of these findings for the understanding of the systems and their changes over time. We also outline new approaches (e.g. experiments, monitoring of key ecological processes like the water pathways in the vegetation, as well as automatised monitoring) to be applied in the ongoing monitoring activities.

Resumo: A região do SASSCAL é o lar de uma biodiversidade muito rica, a qual fornece um valor económico e intrínseco significativo à sociedade humana. No entanto, esta biodiversidade está sujeita a múltiplas pressões emergentes do uso da terra pelo Homem e das alterações climáticas, o que leva à perda da biodiversidade a uma escala substancial. Para avaliar o estado actual e as alterações da biodiversidade na região do SASSCAL, foi implementada uma rede de observação de biodiversidade padronizada. A rede é composta por 47 observatórios de biodiversidade e 10 observatórios auxiliares, onde as mudanças da biodiversidade são monitorizadas no contexto de uma abordagem padronizada. A rede cobre actualmente Angola, Namíbia, Zâmbia e África do Sul.

Os observatórios recém-estabelecidos em Angola e na Zâmbia forneceram dados de referência urgentemente necessários sobre os inventários das espécies de flora e fauna para as áreas de estudo. Os observatórios na Namíbia e África do Sul já existem há 17 ou até mesmo 30 anos, e fornecem informações importantes sobre a complexidade dos sistemas biodiversos e os seus catalizadores.

Fornecemos uma visão geral dos resultados da avaliação da biodiversidade e do trabalho de monitorização nos observatórios. Discutimos o contributo destas descobertas para a compreensão dos sistemas e suas alterações ao longo do tempo. Descrevemos também novas abordagens (e.x.: experiências, monitorização de processos ecológicos chave, tais como percursos da água na vegetação, bem como monitorização automatizada) para serem aplicadas nas actividades de monitorização em curso.

Preface

This article deals primarily with the biodiversity monitoring activities in the geographical space encompassing Angola, Zambia, and Namibia. For South Africa, only activities in the Succulent Karoo Biome of Namaqualand are described; it would be too ambitious to review the wealth of monitoring projects and publications produced by the South African scientific community for the Republic as a whole.

Introduction – the many needs and demands for biodiversity monitoring

The SASSCAL region houses a rich biodiversity and the value of biodiversity is acknowledged in many ways. The species richness of charismatic mammals and birds is the foundation of a large and still growing ecotourism industry. The diversity of plants and insects drives many ecosystem functions and services that support a diversity of agricultural land uses. There is also a diversity of bacteria, fungi, and algae that contribute to soil fertility and nutrient cycling. A wide range of plant and animal species are used commercially. The traditional market products like meat and timber are further complemented by a growing number of new and specialised medicinal, cosmetic, artisanal, and other products.

From a species conservation perspective, the SASSCAL region is home to many important and/or threatened wildlife species like African bush elephant, African forest elephant, southern giraffe, Masai giraffe, cheetah, wild dog, lion, and the largest remaining population of black rhino and other rare species (Western & Vigne, 1985; Emslie & Brooks, 1999; Fennessy et al., 2016). Evolutionary history has created plants and animals with many extraordinary adaptations such as the highly succulent plants commonly known as "living stones" or *Psammotermes* sand termites that create "fairy circles". Furthermore, "living fossils" such as *Welwitschia mirabilis* have survived until today.

In awareness of the importance of the various ecosystem services which depend on biodiversity, all SASSCAL countries are signatories to the Convention on Biological Diversity (CBD). The Ministries of Environment of these countries lead action to protect their country's biodiversity. There are also a large number of international institutions and NGOs that contribute to the conservation and management of biodiversity in the region.

The above-mentioned economic and intrinsic values of biodiversity underline the need to keep stock of these values and to monitor changes in their quantity and quality. Due to their very different purposes and uses, different approaches are needed to monitor the state of biodiversity. It makes a difference whether a farmer community assesses the number of valuable timber trees within their conversancy in order to define the number of trees that can be harvested in a sustainable land use system. It also matters that a country fulfils its reporting duties to the Convention on Biodiversity. However, in order to carry out these different activities, whether at local or national scale, it is required that a number of different variables need to be recorded accurately.

In addition to all the above-mentioned aspects of biodiversity and its changes, we now also have to consider the role that rapid anthropogenic climate change plays as an important driver of changes to ecosystem properties as well as biodiversity.

Therefore, it is important to establish standardised methods for long-term monitoring of biodiversity and ecosystems. Together with existing meteorological recording, this monitoring will allow for the impact of climate change to be assessed against other drivers, especially those related to land use.

With regard to the SASSCAL region and its domination by arid ecosystems, the need for long-term monitoring is of even greater importance. This is because of the high spatio-temporal variability of arid systems, the impact of stochastic processes and rare events, as well as the slow response of many of the organisms and ecosystems to environmental change. The development of monitoring methods that are appropriate for different purposes is itself a subject of research.

Unpacking monitoring: the first step towards monitoring is the assessment of baseline knowledge

When dealing with biodiversity and its long-term changes, it is important first of all to have an overview of what exists, in what quantity and quality, and where it occurs. Although southern Africa has been subject to early scientific explorations (e.g. Baum 1903; Dinter, 1927; Pole Evans, 1948) followed by modern checklists and taxonomic studies, we are still a long way from having a holistic picture of the region and how it has changed over time. While South Africa plays a special role and has been explored relatively systematically (e.g. Acocks, 1988; Mucina & Rutherford, 2006), other parts of the region are still under-researched, some of them very much so.

Basic information on biodiversity is provided by simple checklists based on thorough assessments. They are essential tools in biodiversity research. A checklist provides an inventory of a particular taxonomic group for a given area. Taking the example of plants, the first checklist for Angola was published only in 2008: Plants of Angola – Plantas de Angola by Figueiredo & Smith. For other taxonomic groups and regions, such checklists are still unavailable or are currently in the process of being compiled or amended, for example on herpetofauna (Baptista et al., 2018, this volume) and Checklist Zambia Baltodea (Mbata, 2018, this volume).

Similarly, a full understanding of the spatial extension of vegetation units also provides a baseline assessment that can be used later to identify spatial changes. In this volume the state of the art with regard to vegetation mapping and classification is presented for the Huíla Province, Angola (Chissingui et al, 2018, this volume) and for south-west Botswana (Thireletso, 2018, this volume). In Namibia, vegetation surveying is well advanced with over 12,000 surveyed plots. Also, several regional descriptions have been published in this country over the past few years, or are in the process of being published (e.g. Strohbach, 2013, 2014, 2017d). Here, the work is advancing from making pure

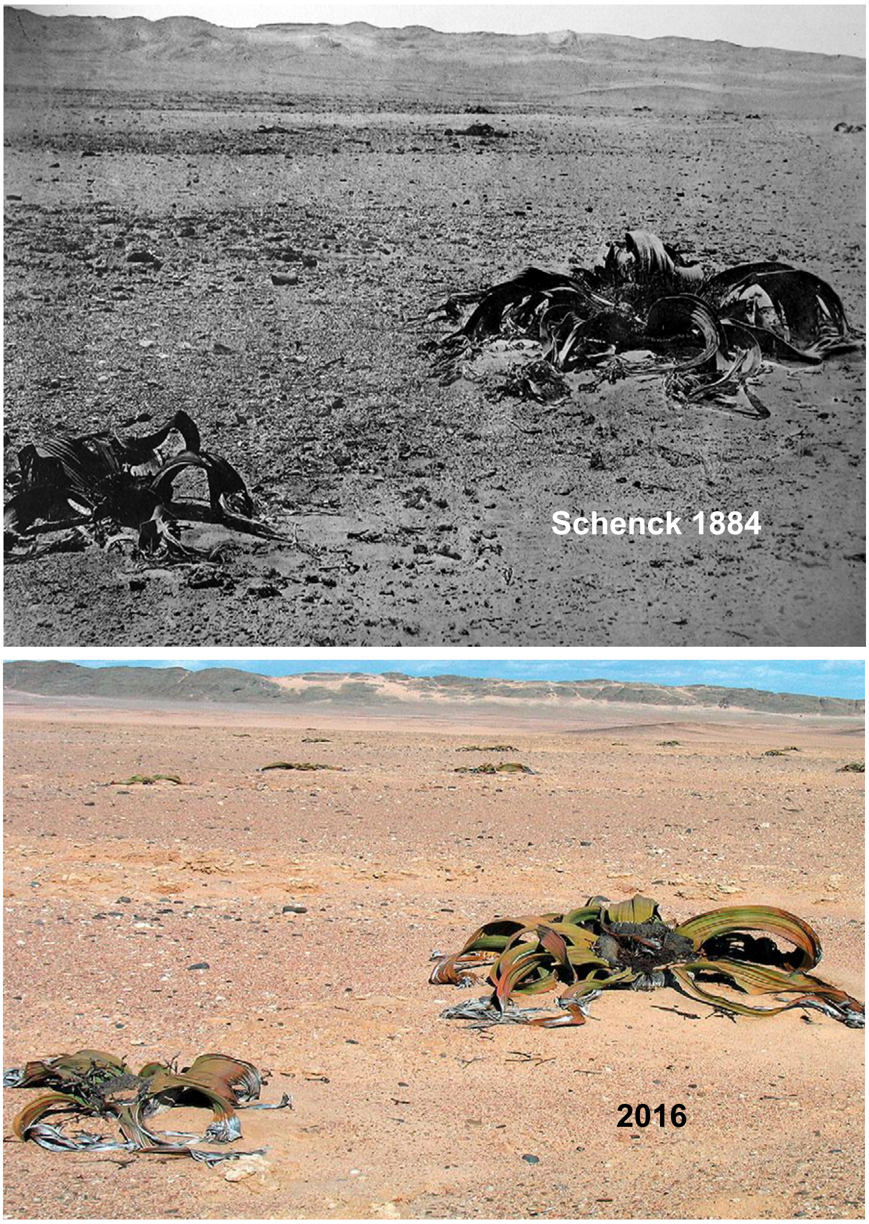


Figure 1: Repeat photography allows comparison over long periods of time. Welwitschia population near the Swakop River (1884 and 2016) (Observatory Welwitschia Vlakte (A09).

baseline descriptions to developing a tool for land use planning (Strohbach, 2017c).

Different approaches to monitoring

In principle, monitoring always aims at detecting, measuring, and understanding change in time. Most current approaches to managing biodiversity are based on interpreting temporal changes in biodiversity, although they often differ in format and content.

Some approaches to studying temporal changes aim at a historical understanding of the origin of the current biodiversity. A vast body of literature describes the presence of wildlife during pre-colonial times. The formerly much wider ranges of large mammals makes us aware of the extent to which their populations have shrunk as a result of human appropriation of productive ecosystems. Taking photographs as replicates of those in historical archives allows us to look backwards in time (Fig. 1), and understand slow changes driven by land use or climate change.

However, the majority of monitoring approaches do not use a retrospective view but instead record biodiversity data in the present time. In this article we explore the latter type of scientific monitoring with a focus on activities in this millennium. We use the current approaches to Essential Biodiversity Variables (EBV, Pereira et al., 2013) and biodiversity indicators (Geijzendorffer et al., 2015). We follow Proença et al. (2016) by classifying sources of primary observations into four types: extensive monitoring schemes, intensive ones, ecological field studies, and satellite and drone remote sensing.

Extensive ground-based monitoring

Extensive monitoring maximises input towards a clear focused goal, while limiting sampling effort on additional site parameters (see also Couvet et al., 2011, for a more detailed discussion). Such an approach is necessary when the management of farming systems or conservation areas is the immediate goal of the monitoring activities. In these cases, focused data that describe the quantity or quality of the managed subject or system are needed. Rapid interpretation of the data allows immediate responses in terms of management decisions. For example, regular game counts from the ground or the air are an important indicator of the effectiveness of previous management decisions. Modern apps allow the growing dimension of civil society-based monitoring. In response to the intensified poaching for animals such as rhino, elephant, and pangolin, targeted monitoring with drones and planes has been undertaken in those regions most threatened by poachers. Threatened species are also monitored with modern tools like GPS collars, camera traps for game, and time lapse cameras. Some examples for game count access can be found at the following websites: http://www.landscapesnamibia.org/sossusvlei-namib/game-counts; http://www.nacso.org.na/resources/game-count-data.

The above activities are typically focused on: (a) threatened or iconic larger animals that are important for conservation and ecotourism, including long distance migratory species; (b) the size and number of populations; and often (c) within geographically or politically defined management units, for example

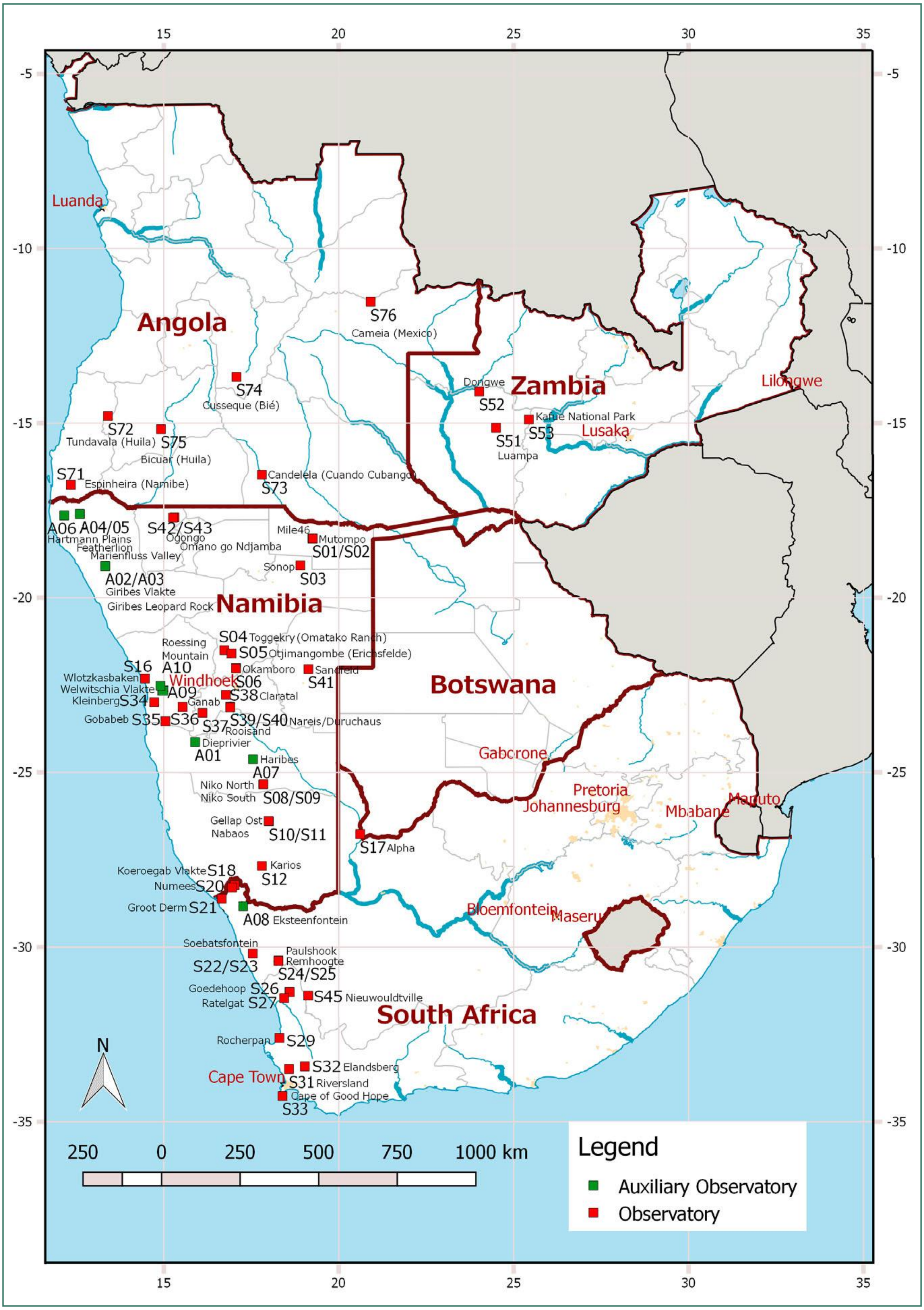


Figure 2: Location of the 57 current Biodiversity Observatories.

Table 1: Biodiversity Observatories within the SASSCAL Observation Net. Rainfall regime: S = summer rainfall, W = winter rainfall, MAP = mean annual precipitation (mm)

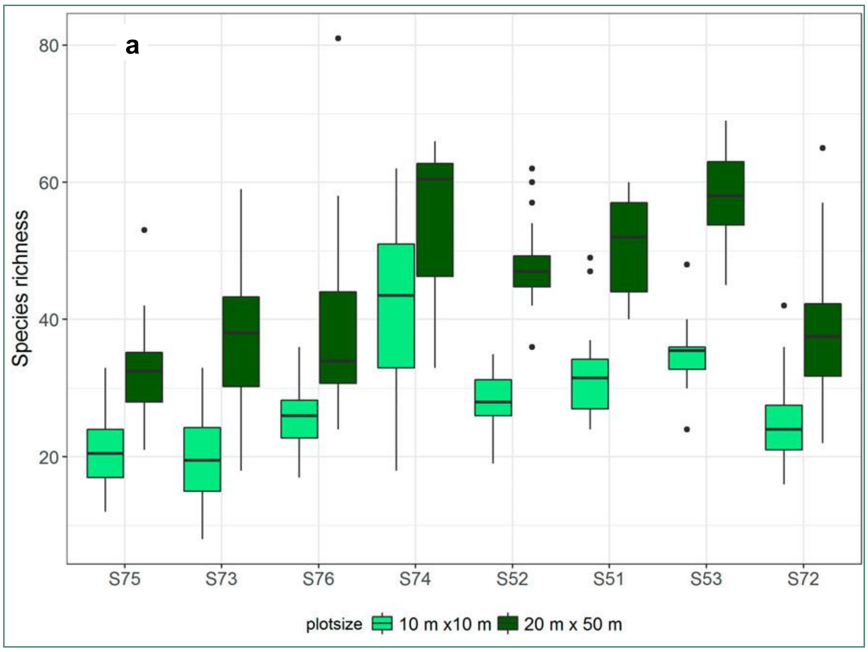
Country	Name	No.	Year of Impl.	Ecoregion	Altitude a.s.l. [m]	Land use type	Rainfall regime	MAP
Angola	Espinheira (Namibe)	S71	2015	Kaokoveld Desert	442	Conservation	S	~100
Angola	Tundavala (Huíla)	S72	2014	Angolan montane forest-grassland mosaic	2250	Pasture, wood cutting, charcoal	S	~1400
Angola	Candelela (Cuando Cubango)	S73	2013	Zambezian Baikiaea woodland	1133	Grazing, slash and burn agriculture	S	~730
Angola	Cusseque (Bié)	S74	2013	Angolan Miombo woodlands	1572	Slash and burn agriculture, woodcutting, charcoal	S	~1000
Angola	Bicuar (Huíla)	S75	2015	Angolan Miombo woodlands	1220	Conservation	S	~650
Angola	Cameia (Moxico)	S76	2016	Western Zambezian Grasslands	1132	Conservation, grazing	S	~900
Namibia	Mile 46	S01	2001	Zambezian Baikiaea woodland	1180	Research faming for cattle breeding	S	527
Namibia	Mutompo	S02	2001	Zambezian Baikiaea woodland	1180	Cropping and cattle grazing	S	527
Namibia	Sonop	S03	2001	Kalahari Acacia-Baikiaea woodlands	1236	Experimental farming with cattle, game	S	498
Namibia	Toggekry (Omatako Ranch)	S04	2001	Kalahari xeric savanna	1519	Farming for game hunting	S	346
Namibia	Otjimangombe (Erichsfelde)	S05	2001	Kalahari xeric savanna	1495	Farming with cattle, game for hunting	S	346
Namibia	Okamboro	S06	2001	Kalahari xeric savanna	1490	Farming with cattle, goats and sheep	S	~400
Namibia	Niko North	S08	2001	Namibian savanna woodlands	1070	Farming with goats	S	~200
Namibia	Niko South	S09	2001	Namibian savanna woodlands	1076	Farming with goats	S	~200
Namibia	Gellap Ost	S10	2001	Namibian savanna woodlands	1099	Farming with sheep, cattle, horses	S	183
Namibia	Nabaos	S11	2001	Namibian savanna woodlands	1045	Farming with sheep, goats, donkeys	S	183
Namibia	Karios	S12	2001	Nama Karoo	909	Conservation	S	103
Namibia	Wlotzkasbaken	S16	2001	Namib desert	73	Conservation area	S	~10
Namibia	Kleinberg	S34	2004	Namib desert	188	Conservation area	S	~10
Namibia	Gobabeb	S35	2004	Namib desert	419	Conservation area	S	~50
Namibia	Ganab	S36	2004	Namibian savanna woodlands	995	Conservation area	S	~80
Namibia	Rooisand	S37	2004	Namibian savanna woodlands	1160	Cattle farming and tourism	S	~200
Namibia	Claratal	S38	2004	Kalahari xeric savanna	1865	Farming with cattle and game	S	~300
Namibia	Narais	S39	2004	Kalahari xeric savanna	1624	Farming with cattle	S	289
Namibia	Duruchaus	S40	2004	Kalahari xeric savanna	1614	Farming with cattle and goats	S	289
Namibia	Ogongo	S42	2007	Angolan Mopane woodlands	1103	Demonstration farming with cattle	S	~500
Namibia	Omano go Ndjamba	S43	2007	Angolan Mopane woodlands	1100	Cropping and cattle and small livestock	S	~500
Namibia	Sandveld	S41	2004	Kalahari xeric savanna	1523	Experimental farming with cattle	S	404
Namibia	Dieprivier	A01	2006	Namib Desert	1049	Tourism	S	100
Namibia	Giribes Vlakte	A02	2006	Namib Desert	621	Semi-nomadic farming	S	100
Namibia	Giribes Leopard Rock	A03	2006	Namib Desert	633	Semi-nomadic farming	S	100
Namibia	Featherlion	A04	2006	Namib Desert	583	Semi-nomadic farming	S	200
Namibia	Marienfluss Valley	A05	2006	Namib Desert	566	Semi-nomadic farming	S	200
Namibia	Hartmann Plains	A06	2006	Namib Desert	554	Semi-nomadic farming	S	100
Namibia	Haribes	A07	2010	Nama Karoo	1194	Commercial farm	S	200
Namibia	Welwitschia Plain	A09	2009 (1884)	Namib Desert	437	National Park	S	20
Namibia	Roessing Mountain	A10	2009 (1917)	Namib Desert	467	National Park	S	20
South Africa	Alpha	S17	2001	Kalahari xeric savanna	896	Game farming, conservation	S	192
South Africa	Koeroegab Vlakte	S18	2001	Succulent Karoo, Richtersveld	635	Semi-nomadic farming	W	138
South Africa	Numees	S20	2001	Succulent Karoo, Richtersveld	362	Semi-nomadic farming with goats, sheep, cattle	W	114
South Africa	Groot Derm	S21	2001	Succulent Karoo, Sandveld	193	Communal small-livestock farming	W	84
South Africa	Soebatsfontein	S22	2001	Succulent Karoo, Hardeveld	392	Communal small-livestock farming	W	131
South Africa	Soebatsfontein	S23	2004	Succulent Karoo, Hardeveld	392	Exclosure	W	131
South Africa	Paulshoek	S24	2001	Succulent Karoo, Kamiesberg	1048	Communal small-livestock farming	W	168
South Africa	Remhoogte	S25	2001	Succulent Karoo, Kamiesberg	1027	Commercial small-livestock farming	W	168
South Africa	Goedehoop	S26	2001	Succulent Karoo, Knersvlakte	245	Conservation	W	124
South Africa	Ratelgat	S27	2001	Succulent Karoo, Knersvlakte	239	Conservation	W	124
South Africa	Moedverloren	S28	2001	Succulent Karoo, Knersvlakte	140	Conservation	W	131
South Africa	Rocherpan	S29	2001	Lowland fynbos and renosterveld	35	Conservation area	W	251
South Africa	Riverlands	S31	2001	Lowland fynbos and renosterveld	140	Conservation area	W	453
South Africa	Elandsberg	S32	2001	Lowland fynbos and renosterveld	95	Conservation area	W	560
South Africa	Cape of Good Hope	S33	2001	Montane fynbos and renosterveld	83	Conservation area	W	689
South Africa	Nieuwoudtville	S45	2007	Conservation area	722	Conservation area	W	301
South Africa	Eksteenfontein	A08	2001	Succulent Karoo, Richtersveld	622	Communal small-livestock farming	W	~200
Zambia	Luampa	S51	2014	Central Zambezian Miombo Woodlands	1148	Forest reserve and crop farming	S	~1150
Zambia	Dongwe	S52	2014	Central Zambezian Miombo Woodlands	1066	Forest reserve and forestry	S	~1100
Zambia	Kafue National Park	S53	2014	Central Zambezian Miombo Woodlands	1210	National Park	S	~1150

conservancies. In summary, these monitoring schemes could be called 'applied monitoring' because data are generated for a concrete and direct management goal within a short timeframe.

Intensive ground-based monitoring

Less common than extensive monitoring schemes are monitoring schemes that observe changes in: (a) less visible animals such as insects; (b) higher plants; (c) mosses, lichens, fungi, algae or bacteria; (d) communities of particular taxonomic groups (or of all organisms); and (e) ecosystem functions and services. In many of the above cases, changes within populations and communities are interpreted as a response to environmental change. These approaches meet the definition of intensive monitoring schemes. Again, following Proença et al. (2016), the goal of these approaches is "to capture ecological responses to environmental change, by monitoring ecosystem functioning and species interactions". The outcomes of these approaches will ultimately also allow application and utilisation for management, although in an indirect and more complex way. To some extent, they can also be regarded as pure research because they are driven by a curiosity in the fundamental rules and processes of living ecosystems.

One of the largest intensive monitoring schemes, and the only one that is regionally integrated, is the SASSCAL Observation Net. This presently comprises 47 biodiversity observatories and 10 auxiliary observatories ranging from central Angola and western Zambia to the northern and western Cape of South Africa (see Fig. 2). Here, standardised fixed-site observations are made within real landscapes at a size of one square kilometre, subdivided and permanently marked with metal poles and metal numbers into 100 hectare cells. For more detail on the layout of the observatories and sampling design, see Jürgens et al. (2012). In a number of landscapes, two of these square kilometre observatories are placed next to each other but are subject to different land-use practices or intensities, in order to compare their impact on biodiversity (Hanke et al., 2014).



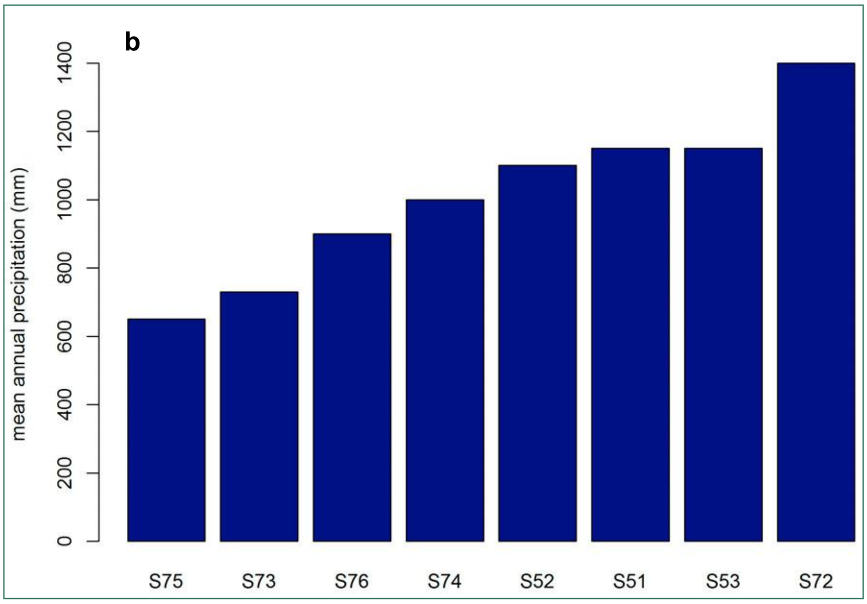


Figure 3: (a) Species richness at the newly established observatories in Angola and Zambia in the 100 m² plots and the 1000 m² plots. Note that the data were collected in different years. n = 20 plots per observatory, except for the 1000 m² plots at observatory S74 where only 6 plots were included. For location and detailed information on the observatories see Table 1 and Figure 2; (b) mean annual precipitation at the observatories.

Ground-based monitoring in Namibia

In Namibia, a total of 22 biodiversity observatories and 9 auxiliary observatories were established during the BIOTA project (2001–2010) (Jürgens et al., 2010). Of these, eleven are in the extremely arid Central Namib and show continuity over the decades due to the rarity of rainfall in combination with the longevity of species like *Welwitschia mirabilis* (see, for example, Jürgens, 2006; Jürgens et al., 2013) (Fig. 1). The two closest observatories to the west coast (Kleinberg and Wlotskas Baken) are of particular interest due to the dynamics of the lichen fields associated with the fogs created by the cold Benguela current around the western coast of southern Africa. The remaining 20 biodiversity and auxiliary observatories are arranged along a north–south transect, and two shorter east–west ones, following the predominant rainfall gradients.

Eleven of the 22 biodiversity observatories in Namibia have been ear-marked as high-priority observatories, with their vegetation having been re-surveyed every year since 2001. These are, from north to south, the observatory pair Mile 46 (S01) and Mutompo (S02), Sonop (S03), the pair Toggekry (Omatako Ranch – S04) and Otjimangombe (Erichsfelde – S05), Sandveld (S41), the pair Narais (S39) and Duruchaus (S40), the pair Gellap Ost (S10) and Nabaos (S11), and finally Karios (S12) (Tab. 1). The dynamics of the four observatories within the Kalahari basin (Mile 46, Mutompo, Sonop, and Sandveld) were compared making use of the full time series (Shidolo, 2017). The phanerophytic (i.e. woody) vegetation proved to be stable overall, but we were able to show considerable shifts in the composition of especially the grass layer, which appears closely related to annual rainfall fluctuations and fire events. Surprisingly, the more arid Sandveld proved to be far more stable than the moister northern observatories of Sonop, Mile 46, and Mutompo. Processing of the available long-term data, collected by five different observers over the past 17 years, showed a high degree of observer bias. The observer bias is evident especially in the identification of minor species, but also in the abundance ratings of the dominant species. Thus, the thorough documentation of all observed taxa underpinned by herbarium specimen is a necessary requirement for meaningful long term monitoring. The abundance rating of the dominant species is another parameter which seems prone to observer bias.

On the main observatories, we also managed to undertake a survey of tortoises as part of the ongoing effort to collect baseline data on additional taxonomic groups (Amutenya, 2016). In addition to these regular surveys, we resurveyed the Gobabeb observatory in 2017. This was done in collaboration with Gobabeb Research and Training Centre, in support of their FogNet initiative. As part of the drone surveying (see below), we identified at each FogNet weather station a square kilometre that can be used as a biodiversity observatory. Using drone imagery, we were able to demarcate habitats, subdivide the square kilometre into 100 one hectare plots, and rank these according to the regular ranking scheme. No physical on-the-ground demarcation has yet been undertaken, but we also collected aerial imagery for baseline data for the Aussaninas, Vogelfederberg, and Garnet Koppie observatories.

At the Karios observatory, in addition to the standard protocol, a more detailed, individual-based monitoring was carried out at the scales of 1000 m², 100 m², 10 m², and 1 m². At the auxiliary observatories of Dieprivier, Giribesvlakte, Leopard Rock, Hartmann Dunes, and Featherlion Hill/ Marienfluss Valley, annual vegetation records and automatic soil humidity measurement were recorded in combination with faunal records. In addition to the annual vegetation monitoring, on the Karios (S12) observatory we annually monitored the arrival, growth, and death of all individuals of perennial plant species.

Ground-based monitoring in Angola

The first biodiversity observatories in Angola, Candelela (S73) and Cusseque (S74), were installed in 2013. Thereafter, four others were added following the BIOTA south–north mega-transect and integrated with the regional network of biodiversity observatories (see Tab. 1). All are located in the southern part of the country (between -11.5° S and -16.8° S latitude and 20.9° E and 12.4° E longitude), and represent four different ecological regions (Burgess et al., 2014). The altitude varies from about 400 m to more than 2200 m above sea level, and mean annual rainfall is in the range 60–100 mm (S71) to 1250–1500 mm (S72).

Annual visits to the observatories have been made in the dry and rainy seasons to record the vascular plant species occurring in the selected plots including their estimated cover, following the BIOTA protocols. Vegetation surveys were carried out, with all vascular plants being recorded, respective checklists prepared, and data stored in BIOTAbase. Specimens are deposited in the herbaria of Lubango (LUB) and Hamburg (HBG), in some cases still awaiting identification. We are currently building a photographic database of all vascular plants occurring at Tundavala Biodiversity Observatory (S72), with the aim of producing a guide to the plants from the Huíla escarpment area. To date, more than 300 different species have been recorded in this observatory, at least 12 of which are endemic to Angola. Figure 3 shows the species richness of vascular plants of the newly-established observatories in Angola and Zambia (for a comparable figure for the other observatories, see Schmiedel et al., 2010). The highest number of species was recorded in the more mesic miombo woodlands (S51–53, S74).

Animal monitoring

In July 2017, a monitoring system for terrestrial mammals using photo-trapping was implemented in a central part of the Bicuar National Park and in the neighbouring observatory (S75). The aim of this approach is to evaluate the patterns and processes determining the structure and functioning of mammalian communities, and the relative importance of resource availability and predation on herbivore behaviour and habitat use. This monitoring system also investigates whether seasonal variation in resource availability regulates herbivore population parameters (CIBIO-UP partnership). In the central area of the park, 49 cameras were arranged in a regular grid of 7 by 7 cameras with a distance between camera locations of ca. 2 km. This allows for a wide spatial coverage in the different types of habitats and ensures the spatial independence of sampling points. This regular design is directly adjacent to an opportunistic sampling scheme of 7 camera sites for the 1 km² observatory. During the dry season in 2017, 33 mammal species were identified with this combined approach. This monitoring scheme continued during the rainy season of 2017/2018.

The Tundavala observatory (S72) is located in a key region of the Angolan escarpment where high animal and plant endemism is recognised (Hall, 1960; Huntley & Matos, 1994). The herpetofauna has been monitored since April 2016 using traplines with pitfalls and funneltraps, as well as visual encounter surveys. Several scientifically interesting species have been registered, some being new records for Angola and species not sighted for decades. The specimens are being deposited in ISCED's new herpetological collection. In Bicuar (S75) and Cusseque (S74), the survey so far comprises a number of non-standardised sampling seasons and opportunistic records. In the Cameia (S76) and Candelela (S73) observatories, the records of herpetofauna are based on opportunistic sampling. Information on the herpetofauna of the Angolan biodiversity observatories is accessible vía the website of the SASSCAL Observation Net (www.sasscalobservationnet.org; see infobox by Hillmann et al., 2018).

Ground-based monitoring in Zambia

To extend the existing network of standardised biodiversity observatories in southern Africa, three biodiversity observatories were established in western Zambia in 2014, following the spatial design and methodology of the BIOTA protocol (Jürgens et al., 2010). All the sites fall within the Miombo Woodland sensu White (1983) and extend over latitudes S 14°–16° and longitudes E 24°–26° at an elevation ranging from 1068 to 1210 metres above sea level (Tab. 1; Fig. 2). The three observatories differ in their land-use type and intensity.

These observatories were installed and assessed during the growing season of 2014 with the intention of providing benchmark data on vascular plant diversity from each site. For each of the plots, the presence of vascular plant species, their cover, and their abundances were recorded. Additionally, of tree height and diameter at breast height (DBH) biometric data were collected for all tree species with DBH >5 cm, with the aim of estimating the above-ground tree biomass. When the species identification is completed, voucher specimens will be lodged at the Herbarium Hamburgense (HBG) and at the Herbarium of the University of Zambia (UZL).

Ground-based vegetation monitoring in South Africa

The 16 biodiversity observatories and one auxiliary observatory in South Africa are located along a north–south transect from the Cape of Good Hope to the Richtersveld in the north-west of South Africa. The transect describes a gradient of decreasing annual rainfall, which in this western part of South Africa mainly falls during the cool winter season between May and August. The mean annual rainfall along the transect ranges from 700 mm at the Cape Peninsula to <100 mm in the Richtersveld (Jürgens et al., 2010). Only one of the South African observatories is located in the summer rainfall region of South Africa, namely at the southern fringe of the Kalahari. For the SASSCAL research activities, special attention has been paid to the ten observatories in the semi-arid and arid part of the winter rainfall gradient of the country, and on the observatory in the southern Kalahari. The winter rainfall observatories represent five bioregions (Tab. 1).

The observatories in the semi-arid to arid winter rainfall region of South Africa fall within the Succulent Karoo biome, which is a renowned biodiversity hotspot (Mucina et al., 2006). It is therefore not surprising that the number of species per 100 m² plot of our Succulent Karoo observatories can reach 50 to 60, and that the cumulative species number per observatory over a period of 17 years lies well above 350 species for most of the observatories (e.g. 398 spp. for observatory Remhoogte (S25)). Many of the species are cryptic in nature, being tiny, well-camouflaged (like the popular “living stones”), found growing inside other plants, and/or strongly resembling each other morphologically. The monitoring of the observatories was hence done on the ground and involved annual visits to each plot to record the cover and (for the 100 m² plots) abundance of individuals of all vascular plant species present in the plot. Two local citizens, who have been trained over several years as para-ecologists (Schmiedel et al., 2016), supported the time-consuming annual field work by counting and recording the abundance of individuals per species.

We analysed the monitoring data of the observatories for patterns of vegetation dynamics in response to inter-annual variation in weather conditions and land use. The current state of the analysis already highlights the complexity of the vegetation dynamics and its drivers in these diverse systems. At the Soebatsfontein observatory (S22) in the Namaqualand Hardeveld bioregion, the vegetation response to the release from high land-use pressure at the beginning of the monitoring activity varied with habitat type, the particular environmental conditions of the plot, and the species that dominated the vegetation (Schmiedel & Oldeland, 2018). Further investigations into the species-specific response to the inter-annual variation in seasonal and total annual rainfall revealed that the total annual rainfall did not affect the abundance of individuals per species for a given year. Instead, the abundance of individuals per species depended on the rainfall amount received during certain seasons. Rainfall during the late summer (between January and March) turned out to be critical in determining the abundance of many of the perennial species. It is assumed that the amount of rainfall received towards the end of the dry period in the winter-rainfall region is critical for the survival, in particular, of the newly established individuals of many of the species (Schmiedel, unpublished data). The analysis of the vegetation monitoring data of the South African Kalahari observatory at the game farm Alpha (S17) showed the joint effect of annual rainfall and game density on total vegetation cover, grass and shrub/ tree cover, and species richness (Jacke, 2016).

Complete vegetation surveys were also carried for the northern-most observatories within the Succulent Karoo biome in South Africa, Numees (S20) and Koeroegab Vlakte (S18) and Groot Derm (S21). However, in this region the annual monitoring scheme deviates from the standardised design and focuses on 45 permanent plots of 10 m x 10 m (100 m²) as well as experimental exclosures (protected from grazing) that have been established here and have been monitored intermittently since 1980. These are regarded as being of high value because of their age, warranting the different design. These plots showed recovery after a drought in 1979/1980 and high continuity during the subsequent 30+ years. Since 2016, however, there has been a drastic decline in the composition and cover of vegetation in the plots due to a major drought. In 2017, the winter rainfall was completely absent from the Richtersveld and many of the permanent observation plots lost all their vegetation. This is the

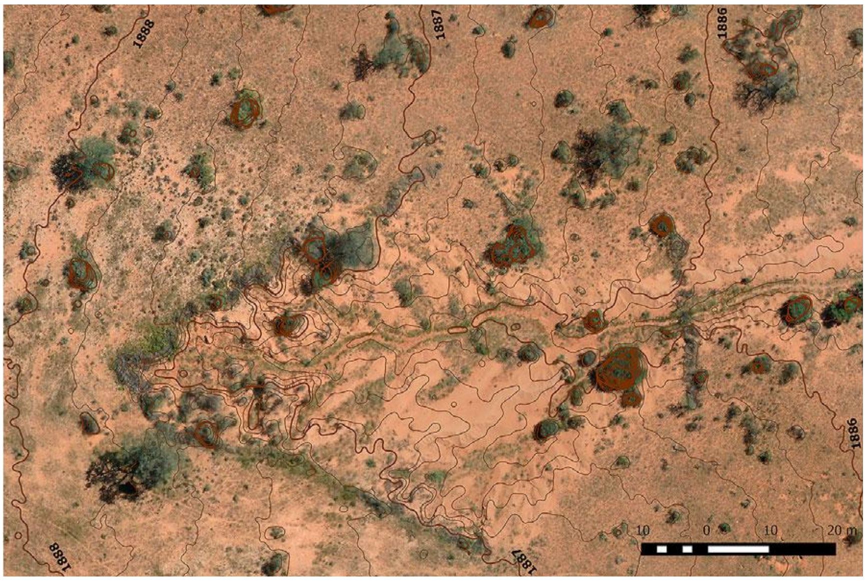


Figure 4: An erosion feature on the Farm Krumhuk outside Windhoek, with a brush filter as counter measure along its head (April 2016). With the calculated DSM we are able to illustrate sub-metre height differences.

harshest drought of the last half century and it is scientifically very interesting to record the longest surviving plant species and the response of the animals and the stock farmers.

In addition to the annual vegetation monitoring, on four observatories in Namaqualand we selected five 100 m² plots where we annually monitored the arrival, growth, and death of all individuals of perennial plant species. This was also performed at all of the 100 m² sites in the Richtersveld. For this purpose, each individual has an identification number and its coordinates locate the plant on the plot map. The individual-based monitoring provides critical information on the year of arrival of the newly-established individuals, their growth rates, year of death, and thus life span. In this way, we get a better understanding of the population dynamics, and can deduce which climatic or other events facilitate the establishment and cause the die-back of individuals of different species. Such detailed data on population dynamics are extremely scarce even though they are also extremely valuable for the interpretation of species turnover and vegetation change under climate change conditions. Previous analyses of long-term individual-based monitoring

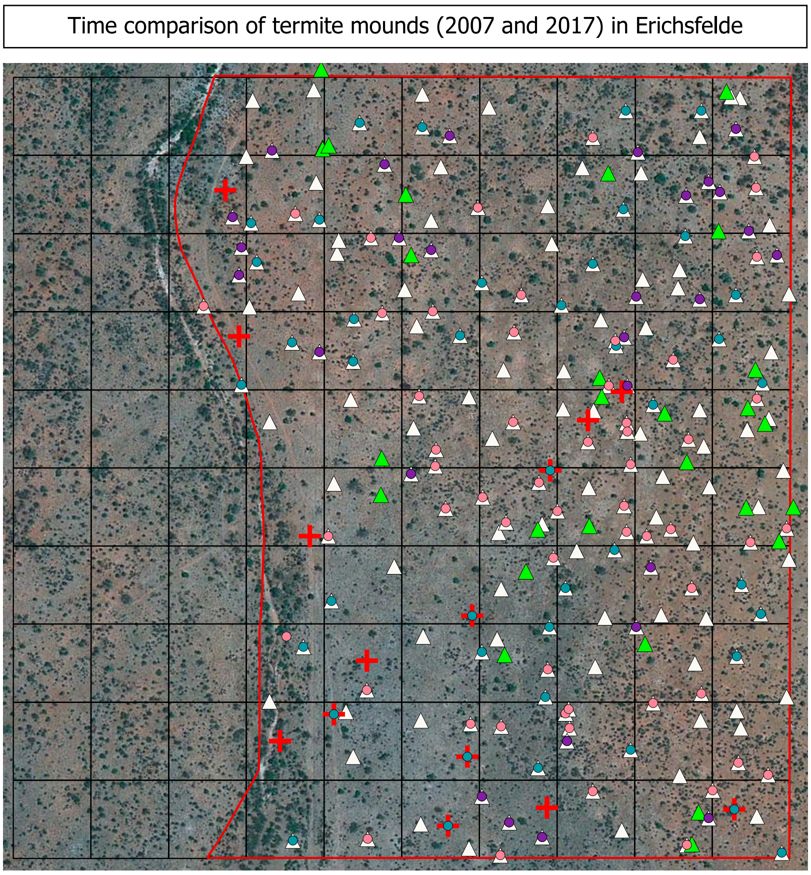
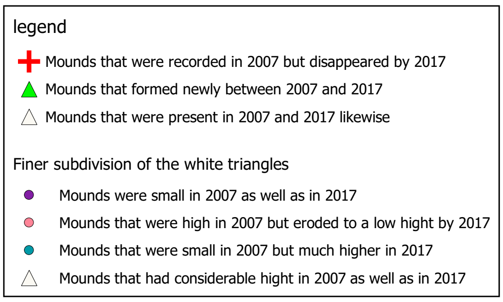


Figure 5: Turnover of mounds of *Macrotermes michaelsii* on the Farm Erichsfelde north of Okahandja in Namibia between 2007 and 2017 (Lisa-Marie Hahn, unpublished). What does it mean that during this decade new termitaria (green triangles) only formed on the non-calcareous soil in the north-east but not on the calcrete in the south centre nor along the river bed in the west? Do the termites respond to bush encroachment? What will the consequence be for future fire dynamics in the area with fewer termite mounds?



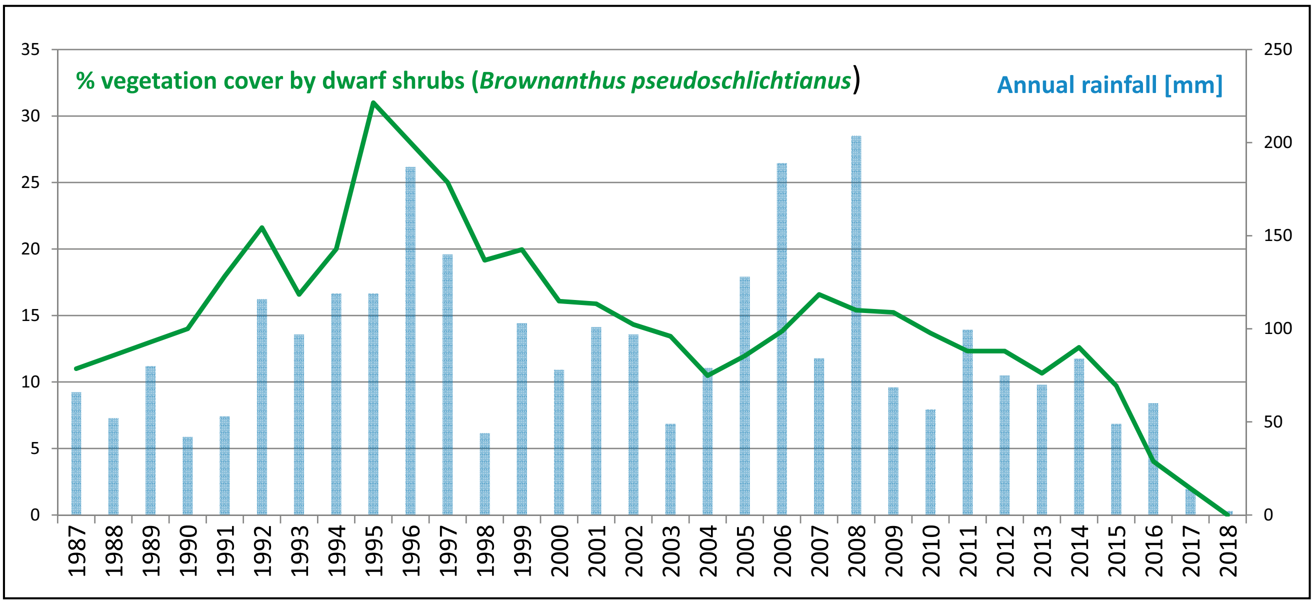


Figure 6: One of several hundred time series that show the impact of the present extreme drought in the northern and western Cape on vegetation. The green line shows the measured cover of vegetation, while the columns represent the annual rainfall. The variability observed in both rainfall and vegetation cover during the last three decades has recently been replaced by a strong decline in both, and agriculture utilisation has come to an end. (Example from the valley of Numees, Richtersveld National Park).

from the Succulent Karoo (Jürgens et al., 1999; Schmiedel et al., 2012), have already provided valuable insight into the drivers of the population dynamics of the endemic flora in the Succulent Karoo.

Drone-based remote sensing observation

Because of the obvious difficulties in resurveying all observatories, we decided to at least obtain a regular (annual) photographic record of the observatories. For this reason, a pair of eBee drones (SenseFly) were purchased, equipped with Canon G9X colour cameras (taking photos which can be separated into the three basic bands of red, green, and blue – RGB). Near-infrared (NIR) capability was originally provided by a Canon S110 camera modified with a NIR filter, but we found that these cameras are highly dust sensitive and were destroyed by regular landings in the Namib and the Kalahari. The NIR capability is planned to be replaced with more robust Sequoia cameras. A large amount of practical experience has been compiled in a short practical guide on the use of such drones for biodiversity surveying (Strohbach, 2017 a,b).

Aerial survey data are available for 2016 for 17 observatories as well as the seven additional FogNet stations, and for 2017 for all observatories and FogNet stations with the exception of Okamboro (S06). A basic data processing routine has been worked out as follows. From the RGB images, a digital surface model (DSM) is calculated (i.e. providing heights of individual features such as trees and termite mounds), as well as regular orthophotos (rectified aerial photographs), in GeoTiff and even Google Earth tiles. From both the RGB and the NIR images, a variety of indices can be calculated, which in turn can be used to identify specific features on the ground (see, for example, Oldeland et al., 2017; Strohbach, 2018). The vegetation indices being calculated as standard are the excessive green, normalised excessive green, and excessive red indices derived from RGB images (Meyer & Neto, 2008; Rasmussen et al., 2016), whilst a NDVI and Modified SAVI are also calculated (Huete, 1988; Huete et al., 1992) from the NIR images if available.

First attempts to map tree species to species level are promising (Oldeland et al., 2017), but require more ground-truth data. The aerial images were also successfully used to determine the degree of forest degradation and deforestation in the Mopane savanna in Namibia (Strohbach, 2018), as well as the woodland structure of the Kavango woodlands (Knox et al. 2018). We are also busy determining the compatibility of current high-resolution colour images with old low-resolution, panchromatic aerial photographs, to monitor bush encroachment trends since the 1950s (Walters, 2016).

Monitoring with drone-based aerial imagery is not limited to tree and shrub species. We are able to monitor the density and vigour of the grass sward, an important requirement for grazing monitoring, using remote sensing data. This, in turn, feeds into the ongoing programme to restore Namibian Rangelands (see http://www.nrmps.org, http://www.agra.com.na/news/rangeland-monitoring-project.php and http://www.namibiarangelands.com/). Furthermore, erosion features are both clearly visible and measurable in drone imagery (Fig. 4). Even the response of vegetation and soils to restoration measures can be made visible on NIR imagery.

We are also measuring the success of rehabilitation measures at the B2Gold Oshikoto mine (Strohbach & Hauptfleisch, in prep.), mapping the endemic *Neoluederitzia sericeocarpa* populations in the lower Fish River (Hakalume, 2018), determining location, height and health of termite mounds in savanna ecosystems (Fig. 5), as well as determining regrowth of alien invasive *Prosopis* species at Gibeon. Trials are also undertaken

Figure 7: Experimental fire plot ("Purgatory") at observatory S75 Bicuar National Park on the 12 September 2017. The experimental design comprises thirty-six 15 m x 15 m plots and a 5 m firebreak around the outer border of the experimental site. Early and late fire treatments are recognisable by green vs. dark brown patches. Controls (fire exclosure) are perfectly visible due to the bright orange colour of the mature grass sward.

to determine the number and density of burrows of ground-dwelling mammals, and their effects on grass dynamics (Hauptfleisch et al., 2017; Rodgers et al., 2017), as well as using the drone-based aerial imagery to undertake less-intrusive, automated game counts.

Current key messages from the observatory network

Over the past several years, a substantial effort has been invested in the establishment of the observation network. So far, some of the older time series already cover two or even three decades (e.g. from some observatories in the arid ecosystems of South Africa), which is sufficient for meaningful analyses (see references mentioned above and contributions in this book). Continuous monitoring of the newer observatories in Angola and Zambia will produce similarly valuable data in the future.

With the funding provided through the BIOTA, TFO, and SASSCAL initiatives, it was possible to establish and maintain the Observation Network as an important science infrastructure. Meanwhile, numerous important results have been achieved and presented at international conferences like the GEOSS GEO BON Open Science Conference in 2016. Below, some key messages are briefly outlined, without pre-empting careful data analyses in more extensive publications:

- In none of the observatories has a drastic invasion of exotic organisms been observed to date.
- In the observatories located in Kalahari sands, there is a continuous gradient from rich woodland to much less productive sparse arid vegetation types with fewer perennial grasses, and this may reflect a slow degradation process in time.
- During the observation period the majority of observatories have showed only minor changes. However, the droughts in parts of Namibia in 2015 and 2016 and in the Richtersveld and Namaqualand in 2017 and 2018 have caused a most dramatic – in many places complete – die-back of the vegetation, which has turned previously vegetated landscapes into desert (Fig. 6).
- In addition to a general increase or decrease of rainfall, seasonal changes in rainfall amounts have a major impact on species composition, especially in Namaqualand.
- Frost seems to be a neglected but relevant factor controlling the spatial array of the forest and grassland mosaic on the Central Angolan Plateau. Topoclimatic effects need much stronger attention in order to understand past transitions between savanna and forest states, to support conservation planning efforts, and to optimise agricultural land-use decisions.
- As well as the dominant control by climatic oscillations and land use, biotic interactions also play a major role and may cause cascading effects over many years.
- Termites, and especially the genus *Macrotermes,* are very important ecosystem engineers in savanna ecosystems. The role of their foraging of dead wood should be studied with regard to the management of bush encroachment/clearing and fire.
- Fire plays an important role for the vegetation dynamics of the observatories in the Miombo belt. So far, at least in the Angolan observatories, all observed fires have been of human origin and for land management purposes. Grassland management for hunting or grazing, and slash-and-burn of woodland and forest ecosystems, are among the most frequent causes of fires. Thus, the seasonality and intensity of fires in the observatories are controlled by human land use and not by natural causes.
- The newly developed remote sensing tools to detect ignition points and map spatio-temporal footprints of individual fires (see Röder et al, 2018) should be coupled to the SASSCAL Observation

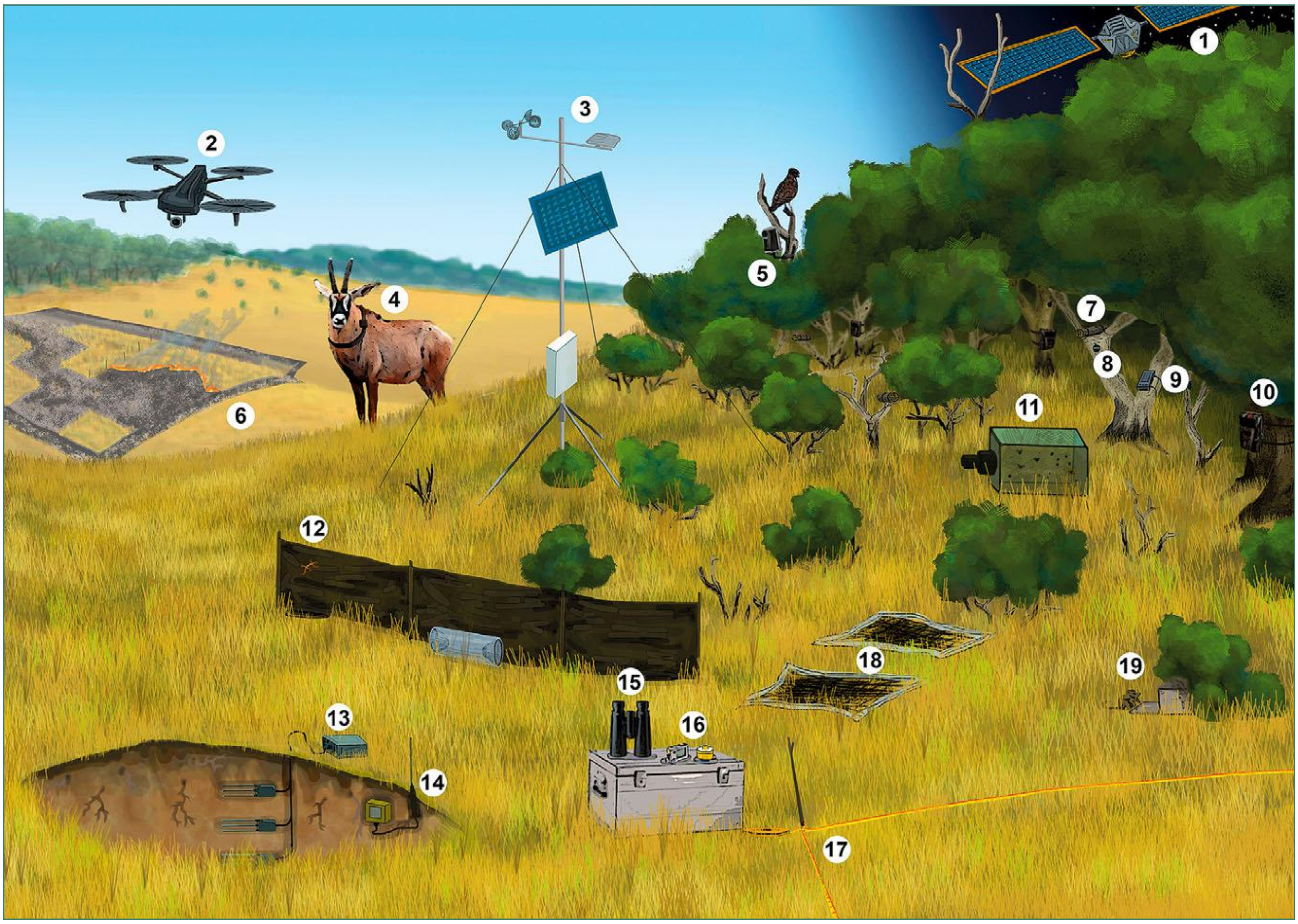


Figure 8: Smart monitoring devices and new experimental approaches for intensive and automatic biodiversity monitoring already in use or planned for SASSCAL Biodiversity Observatories. 1: Imagery/data transfer via satellite; 2: Arial imagery via drones; 3: Climate station; 4: GPS collars; 5: Phenocam; 6: "Purgatory"; 7: Insect trap nests; 8: Tree tagging/permanent marking; 9: Sound recording/bird calls; 10: Camera traps; 11: Photo sensor insect counter; 12: Herpetofauna trapping; 13: Soil water measurements; 14: Temperature loggers; 15: Binoculars/observations; 16: Tree height measurements; 17: Vegetation surveys; 18: Decay monitoring/litter bags; 19: Small mammal monitoring.

Net. They offer new potential for near real-time analyses of fire dynamics and fire impacts on forest and savanna ecosystems.

- Several of the newly established Angolan observatories have lost most of their larger fauna over the last few decades. The extent of faunal depletion and its consequences for vegetation dynamics, fire behaviour and fuel loads, nutrient cycles and spatial nutrient translocation, and ecosystem services for local communities, need urgently scientific attention.

The road ahead

For the future we will need a more functional understanding of the processes of change in order to propose adequate responses. Therefore, we regard it as necessary to integrate more monitoring of (a) key ecological processes and (b) organismic interactions, and to (c) integrate a stronger experimental component. To do the monitoring work more efficiently, we also aim for (d) a stronger use of automatic measuring systems that are made available by technological innovation.

(a) Key ecological process monitoring

In addition to the already established monitoring of variables that describe the quantity and quality of biological organisms, in future we should enhance and integrate the monitoring of environmental variables and processes. Ecohydrological monitoring, which includes the monitoring of water in the topsoil and how it is used by vegetation, could quite easily be established at many of the arid and semi-arid observatories.

(b) Organismic interactions

The decline of insects in Europe has recently increased awareness of how important insects and birds are for ecosystem functions and services. The key services of insects and birds are not only related to plant pollination and seed dispersal, but also the ecosystem engineering functions of termites and ants, which drive soil fertility and productivity and, in so doing, influence the fire regimes of African savannas.

(c) Experiments

Apart from the original grazing exclosures and range management experiments, which were included at the start of our activities in the region, additional experimental approaches have already been integrated in the Observation System to a certain extent. Dantas et al. (2016) pointed to the role of fire as a key mechanism in maintaining the balance between alternate biome states in tropical ecosystems of West Africa. If fire is indeed a tipping mechanism between savannas and woodlands, we need a sound understanding of the differences between man-made and natural fire regimes in terms of seasonal timing, return period, fire intensity, and fire patterns. We also need to understand what the respective consequences of human-dominated fire regimes might be for the resilience of Africa's forest and woodland ecosystems. At present, well documented long term fire experiments from Afrotropical grasslands are rather scarce, the long term fire plots in South Africas Kruger National Park being the most prominent example (van Wilgen et al. 2007).

So far, we have established systematic fire experiments in the geoxylic grasslands of the Angolan observatories Cusseque (S74) and Bicuar National Park (S75), which are located in direct proximity to woodland habitats. The experiments follow a randomised block design with three different treatments – early dry season fire ("cold fire"), late dry season fire ("hot fire"), fire exclosure ("control") – and 12 repetitions for each treatment. The experiment is carried out in a 1 ha plot with 36 permanently marked subplots of 15 m x 15 m each and a 5 m firebreak around the outer edge (Fig. 7).

The experimental design allows for analyses of selected functional traits of perennial plants, as well as of performance indicators and species dynamics. Temperature loggers are installed to measure microclimatic patterns and fire heat. Changes in vegetation pattern will be documented at regular intervals with drone photography. In the future, we plan to extend this experimental approach to additional observatories in the Miombo Biome.

(d) Automatic monitoring systems

It is a global trend in biodiversity observation projects to make use of advances in technology to complement existing monitoring activities. Automated data recording and photography, robotic systems, genomic sampling, and sound sensors, are available and have recently become more robust. Such electronically recorded data can be integrated more easily into the existing data framework than in the past, and can even link up with remotely sensed data (Fig. 8).

The following country-specific perspectives can be formulated for the biodiversity monitoring activities in Angola, Namibia, and South Africa:

a) Angola: The first few years of implementation of the standardised biodiversity observatories have enabled us to establish a monitoring network and to build a baseline to carry out essential analyses to understand the current status of biodiversity in the country. The way ahead consists of the analysis of already-accumulated monitoring data in order to provide a better understanding of the dynamics of plant and animal communities, the environmental factors affecting species composition and habitat conditions, and to create comparable data layers on biodiversity status and trends within the region.

We must highlight that Angola faces a number of challenges in making a national biodiversity monitoring system operational. The monitoring system needs to secure the long-term sustainability of the observatory network that is already in place. The effective institutionalisation of the system is needed, as is a comprehensive program to maintain, strengthen, and expand Angola's system of observatories. As local capacity to conduct monitoring and the processing and analysing of data is still our Achilles' heel, we remain committed to continue the empowerment of a new generation of researchers able to address the scientific and technical needs for long-term biodiversity monitoring in the country.

b) Namibia: Although drone surveying proved to be a fast and cost-effective method to obtain baseline data, at best it yields information about the dynamics of individual woody plants and not the composition of the herbaceous and graminoid layers of the vegetation. The effective interpretation of such drone data also requires detailed ground-truth data. Whereas in the past we concentrated on detailed data related to the composition of all vegetation layers, we will in future need to collect additional data on grass sward density and the specific location of individual tree species in order to make the most of drone imagery. However, the potential of this imagery as part of an integrated long-term monitoring system is excellent. Of particular interest will be an extended use of Near Infrared (NIR) and Red Edge imagery available from the Sequoia sensors, once these are available. Here we hope to greatly improve the monitoring of erosion rehabilitation and of lichen field dynamics after highly destructive disturbance events such as off-road driving and the impact of film sets.

c) South Africa: The analyses of monitoring data from the dry regions of South Africa have so far revealed the complexity of the interaction between changes in plant species composition of the vegetation, the population dynamics of individual species, and the environmental drivers such as climate, herbivory, and habitat conditions. Current analyses of time-series data from the Succulent Karoo has revealed that the commonly used classification of plants into so-called life-form types sensu Raunkiaer as plant strategy types is not sufficient to explain the species' responses to the rainfall patterns. We will therefore further refine the classification of life form types for the Succulent Karoo by taking into account traits that are related to the life span of the species and to the strategies of resource allocation. For example, a quick response to high rainfall events versus protection of the water-storing organs against evaporation or herbivory are two extremes along the continuum of traits. With regard to the environmental drivers, we will place greater emphasis on understanding the seasonality of rainfall and the number of rainfall events that have an effect on plant growth (> 6 mm per rainfall event, Hanke et al., 2011) as well as the duration of periods with no efficient rainfall.

The long-term data on vegetation dynamics will further be made available for global analyses on changes in diversity, species, or life form composition. The study has already attracted great interest from researchers all over the world and has contributed, for example, to a global analysis on the influence of mean annual precipitation on the proportion of annual and perennial species in the regional flora (Torma et al., in subm.). Findings from our analyses have also been included in the global PREDICTS database (Projecting Responses of Ecological Diversity in Changing Terrestrial Systems (Hudson et al., 2017), and have contributed to the project "Drivers of communities' temporal stability" of the Czech Academy of Science.

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References

Acocks, J.P.H. (1988) *Veld Types of South Africa*, 3rd Edition. Botanical Research Institute, Department of Agriculture and Water Supply, Pretoria.

Amutenya, K.K. (2016) Home range and thermal analyses of two sympatric tortoise species, *Stigmochelys pardalis* and *Psammobates oculifer* in the Thornbush Savanna of Central Namibia. Masters in Natural Resources Management thesis, Namibia University of Science and Technology.

Baptista, N., António, T. & Branch, W.R. (2018) Amphibians and reptiles of the Tundavala region of the Angolan Escarpment. This volume.

Baum, H. (1903) *Kunene-Sambesi-Expedition*, Verlag des Kolonial-Wirtschaftlichen Kommitees, Berlin.

Burgess, N., Hales, J. D., Underwood, E., Dinerstein, E. et al. (2004). *Terrestrial Ecoregions of Africa and Madagascar – a conservation assessment.* Island Press, Washington DC. 499 pp.

Chissingui, A.V., Gonçalves, F.M.P., Luís, J.C., Tchamba, J.J., Rafael, M.F.F. & Alexandre, J.L.M. (2018) Vegetation survey of the woodlands of Huíla Province. This volume.

Dantas, V. d. L., et al. (2016) Disturbance maintains alternative biome states. *Ecology Letters*, **19**, 12-19.

Dinter, K. (1917-1927) Index der aus Deutsch-Südwestafrika bis zum Jahre 1917 bekannt gewordenen Pflanzenarten. I-XXII. *Feddes Repertorium*.

Emslie, R. & Brooks, M. (1999) *African rhino: status survey and conservation action plan*, IUCN, World Conservation Union, Cambridge, UK.

Fennessy, J., Bidon, T., Reuss, F., Kumar, V., Elkan, P., Nilsson, M.A., Vamberger, M., Fritz, U. & Janke, A. (2016) Multi-locus Analyses Reveal Four Giraffe Species Instead of One. *Current Biology*, **26**, 2543–2549.

Figueiredo, E. & Smith, G.F. (2008) *Plants of Angola/Plantas de Angola.*, South African National Biodiversity Institute.

Hakalume, I. (2018) Assessing the population density of *Neoluederitzia sericocarpa* using aerial imagery in Seeheim, Namibia. Bachelor Honours in Natural Resources Management mini-thesis, Namibia University of Science and Technology.

Hall, B.P. (1960). The faunistic importance of the scarp of Angola. *Ibis* **102**, 420–442.

Hanke, W., Böhner, J., Dreber, N., Jürgens, N., Schmiedel, U., Wesuls, D. & Dengler, J. (2014) The impact of livestock grazing on plant diversity: an analysis across dryland ecosystems and scales in southern Africa. *Ecological Applications*, **24**, 1188-1203.

Hanke, W., Gröngröft, A., Jürgens, N. & Schmiedel, U. (2011) Rehabilitation of arid rangelands: Intensifying water pulses from low-intensity winter rainfall. Journal of Arid Environments, **75**, 185-193.

Hauptfleisch, M., Vinte, M. & Blaum, N. (2017) A comparison of the community dynamics of bioturbating small mammals between livestock and wildlife farming areas in the Kalahari, Namibia. *Namibian Journal of Environment,* Vol 1 (2017)*:*

Hillmann, T., Muche, G., Josenhans, K. & Jürgens, N. (2018) Online presentation of the SASSCAL ObservationNet. This Volume.

Hudson, L.N., Newbold, T., Contu, S. et al. (2017) The database of the PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) project. Ecology and Evolution, **7**, 145-188.

Huete, A.R. (1988) A Soil-Adjusted Vegetation Index (SAVI). *Remote Sensing of Environment*, **25**, 295–309.

Huete, A.R., Hua, G., Qi, J.C. & van Leeuwen, W.J.D. (1992) Normalization of Multidirectional Red and NIR Reflectances with the SAVI. *Remote Sensing of Environment*, **41**, 143–154.

Huntley, B. & Matos, E. (1994) Botanical diversity and its conservation in Angola. *Strelitzia* **1**, 53-74.

Jacke, V. (2016) *Vegetation patterns in space and time on long-term observation plots in the South African Kalahari.* MSc. thesis, University of Hamburg, Hamburg.

Jürgens, N., 2006. Recent change of flora and vegetation in Namibia – a brief review of dynamics drivers and scientific approaches. In: Leser, H. (Ed.), The Changing Culture and Nature of Namibia: Case Studies. The Sixth Namibia Workshop, in Honour of Dr. h. c. Carl Schlettwein (1925–2005), Basel 2005. Basler Afrika Bibliographien, Basel, pp. 91–108.

Jürgens, N., Gotzmann, I.H. & Cowling, R.M. (1999) Remarkable medium-term dynamics of leaf succulent Mesembryanthemaceae shrubs in the winter-rainfall desert of northwestern Namaqualand, South Africa. *Plant Ecology*, **142**, 87-96.

Jürgens, N., Haarmeyer, D.H., Luther-Mosebach, J., Dengler, J., Finckh, M. & Schmiedel, U. eds. (2010) *Patterns at Local Scale: The BIOTA Observatories*, Klaus Hess Publishers, Göttingen & Windhoek.

Jürgens, N., Oldeland, J., Hachfeld, B., Erb, E. & Schultz, C. (2013) Ecology and spatial patterns of large-scale vegetation units within the central Namib Desert. *Journal of Arid Environments*, **93**, 59–79.

Jürgens, N., Schmiedel, U., Haarmeyer, D.H. et al (2012) The BIOTA Biodiversity Observatories in Africa--a standardized framework for large-scale environmental monitoring. *Environmental monitoring and assessment*, 184, 655–78.

Klintenberg P, Seely M. (2004) Land degradation monitoring in Namibia: a first approximation. *Environmental Monitoring and Assessment*, **99**, 5-21.

Mbata, K.J. (2018) Annotated checklist of cockroaches and termites of Zambia (Arthropoda: Insecta; Blattodea). This volume.

Mendelsohn JM, vanderPost C, Ramberg L, Murray-Hudson M, Wolski P & Mosepele K. 2010. Okavango Delta: Floods of Life. RAISON, Windhoek, 1-144.

Meyer, G.E. & Neto, J.C. (2008) Verification of color vegetation indices for automated crop imaging applications. *Computers and Electronics in Agriculture*, **63**, 282–293.

Mucina, L. & Rutherford, M.C. eds. (2006) *The Vegetation of South Africa, Lesotho and Swaziland*, South African National Biodiversity Institute, Pretoria.

Mucina, L., Jürgens, N., Le Roux, A., Rutherford, M.C., Schmiedel, U., Esler, K.J., Powrie, L.W., Desmet, P.G. & Milton, S.J. (2006) Succulent Karoo Biome. The vegetation of South Africa, Lesotho and Swaziland (ed. by L. Mucina and M.C. Rutherford), pp. 221-229. South African National Biodiversity Institute Pretoria.

Oldeland, J., Große-Stoltenberg, A., Naftal, L. & Strohbach, B.J. (2017) *The potential of UAV derived image features for discriminating savannah tree species*. *The Roles of Remote Sensing in Nature Conservation* (ed. by R. Díaz-Delgado, R. Lucas, and C. Hurford), pp. 183–201. Springer International Publishing.

Pole Evans, I.B. (1948) A reconnaissance trip through the eastern portion of the Betchuanaland Protectorate and an expedition to Ngamiland. *Botanical Survey of South Africa*, **21**, 1–73.

Proença, V., Martin, L.J., Pereira, H.M., Fernandez, M., McRae, L., Belnap, J., Böhm, M., Brummitt, N., García-Moreno, J., Gregory, R.D., Honrado, J.P., Jürgens, N., Opige, M., Schmeller, D.S., Tiago, P. & van Swaay, C.A.M. (2016) Global biodiversity monitoring: From data sources to Essential Biodiversity Variables. *Biological Conservation*, **213**, 256-263.

Rasmussen, J., Ntakos, G., Nielsen, J., Svensgaard, J., Poulsen, R.N. & Christensen, S. (2016) Are vegetation indices derived from consumer-grade cameras mounted on UAVs sufficiently reliable for assessing experimental plots? *European Journal of Agronomy*, **74**, 75–92.

Raunkiaer, C. (1937) *Plant life forms*, The Clarendon Press, Oxford.

Rodgers, M., Bilton, M. & Hauptfleisch, M. (2017) Responses and feedbacks of burrowing mammals under differently managed rangelands. *Namibian Journal of Environment,* Vol 1 (2017)

Schmiedel, U., Araya, Y., Bortolotto, M.I., Boeckenhoff, L., Hallwachs, W., Janzen, D., Kolipaka, S.S., Novotny, V., Palm, M., Parfondry, M., Smanis, A. & Toko, P. (2016) Contributions of paraecologists and parataxonomists to research, conservation, and social development. *Conservation Biology*, **30**, 506-519.

Schmiedel, U., Dengler, J. & Etzold, S. (2012) Vegetation dynamics of endemic-rich quartz fields in the Succulent Karoo, South Africa, in response to recent climatic trends. *Journal of Vegetation Science*, **23**, 292–303.

Schmiedel, U., Dengler, J., Luther-Mosebach, J., Gröngröft, A., Muche, G., Petersen, A., Strohbach, B.J. and Jürgens, N. (2010) Patterns and dynamics of vascular plant diversity along the BIOTA transects in southern Africa. In *Biodiversity in southern Africa*, 2, (ed. by Schmiedel, U, & Jürgens, N.) pp.118-135. Klaus Hess Publishers, Göttingen and Windhoek.

Shidolo, E.L.K. (2017) Assessment of vegetation diversity, structure, cover and the influence of fire along the rainfall gradient in the Kalahari, East of Namibia, using long-term data. Masters in Natural Resources Management thesis, Namibia University of Science and Technology.

Strohbach, B. (2017a) Experiences with the eBee Drone Part 1. *SASSCAL News*, **2**, 17–20.

Strohbach, B. (2017b) Experiences with the eBee Drone Part 2. *SASSCAL News*, **2**, 20–23.

Strohbach, B.J. & Hauptfleisch, M.L. (submitted) Rehabilitation success at the Oshikoto Mine, Otjiozondjupa Region in Namibia, as determined with high-resolution NIR aerial imagery. *Namibia Journal of Environment*.

Strohbach, B.J. (2013) Vegetation of the Okavango River valley in Kavango West, Namibia. *Biodiversity & Ecology*, **5**, 321–339.

Strohbach, B.J. (2014) Vegetation of the Eastern Communal Conservancies in Namibia: I. Phytosociological descriptions. *Koedoe - African Protected Area Conservation and Science*, **56**.

Strohbach, B.J. (2017c) Making more of vegetation classification results: A Livestock Farming Suitability Index as tool for Land-Use Planning in Namibia. *Phytocoenologia*, **48**, 7-22.

Strohbach, B.J. (2017d) Vegetation of the Auas-Oanob Conservancy in the Khomas Hochland of Namibia. *Namibian Journal of Environment*, **1**.

Tshireletso, K., Makhabu, S.W., Nsinamwa, M., Kgosiesele, E., Setlalekgomo, M.R., Seletlo, Z., Majaga, S., & Legwatagwata, B. (2018) Diversity patterns of woody vegetation of Kgatleng District, Botswana. This volume.

Van Wilgen, B.W., Govender, N. and Biggs, H.C. (2007) The contribution of fire research to fire management: a critical review of a long-term experiment in the Kruger National Park, South Africa. *International Journal of Wildland Fire*, **16**, 519-530.

Verlinden A., Laamanen R. (2006) Long term fire scar monitoring with remote sensing in Northern Namibia: relations between fire frequency, rainfall, land cover, fire management and trees. *Environmental Monitoring and Assessment,* **112**,231-53.

Walters, M.H. (2016) Determining the changes in vegetation structure in three semi-arid savanna environments in Namibia over the past 60 years. Bachelor Honours in Natural Resources Management mini-thesis, Namibia University of Science and Technology.

Western, D. & Vigne, L. (1985) The deteriorating status of African rhinos. *Oryx*, **19**, 215.

White, F. (1983) *The Vegetation of Africa – A descriptive memoir to accompany the Unesco/AETFAT/UNSO vegetation map of Africa*. United Nations Educational Scientific and Cultural Organisation, Paris. 356 pp.

Wolski, P., Murray-Hudson, M., Thito, K. & Cassidy, L. (2017) Keeping it simple: Monitoring flood extent in large data-poor wetlands using MODIS SWIR data. *International Journal of Applied Earth Observation and Geoinformation*, **57**, 224-234.

References [CrossRef]

Acocks, J.P.H. (1988) *Veld Types of South Africa*, 3rd Edition. Botanical Research Institute, Department of Agriculture and Water Supply, Pretoria.

Amutenya, K.K. (2016) Home range and thermal analyses of two sympatric tortoise species, *Stigmochelys pardalis* and *Psammobates oculifer* in the Thornbush Savanna of Central Namibia. Masters in Natural Resources Management thesis, Namibia University of Science and Technology.

Baptista, N., António, T. & Branch, W.R. (2018) Amphibians and reptiles of the Tundavala region of the Angolan Escarpment. This volume. CrossRef

Baum, H. (1903) *Kunene-Sambesi-Expedition*, Verlag des Kolonial-Wirtschaftlichen Kommitees, Berlin.

Burgess, N., Hales, J. D., Underwood, E., Dinerstein, E. et al. (2004). *Terrestrial Ecoregions of Africa and Madagascar – a conservation assessment.* Island Press, Washington DC. 499 pp.

Chissingui, A.V., Gonçalves, F.M.P., Luís, J.C., Tchamba, J.J., Rafael, M.F.F. & Alexandre, J.L.M. (2018) Vegetation survey of the woodlands of Huíla Province. This volume. CrossRef

Dantas, V. d. L., et al. (2016) Disturbance maintains alternative biome states. *Ecology Letters*, **19**, 12-19. CrossRef

Dinter, K. (1917-1927) Index der aus Deutsch-Südwestafrika bis zum Jahre 1917 bekannt gewordenen Pflanzenarten. I-XXII. *Feddes Repertorium*.

Emslie, R. & Brooks, M. (1999) *African rhino: status survey and conservation action plan*, IUCN, World Conservation Union, Cambridge, UK.

Fennessy, J., Bidon, T., Reuss, F., Kumar, V., Elkan, P., Nilsson, M.A., Vamberger, M., Fritz, U. & Janke, A. (2016) Multi-locus Analyses Reveal Four Giraffe Species Instead of One. *Current Biology*, **26**, 2543–2549. CrossRef

Figueiredo, E. & Smith, G.F. (2008) *Plants of Angola/Plantas de Angola.*, South African National Biodiversity Institute.

Hakalume, I. (2018) Assessing the population density of Neoluederitzia sericocarpa using aerial imagery in Seeheim, Namibia. Bachelor Honours in Natural Resources Management mini-thesis, Namibia University of Science and Technology.

Hall, B.P. (1960). The faunistic importance of the scarp of Angola. *Ibis* **102**, 420–442. CrossRef

Hanke, W., Böhner, J., Dreber, N., Jürgens, N., Schmiedel, U., Wesuls, D. & Dengler, J. (2014) The impact of livestock grazing on plant diversity: an analysis across dryland ecosystems and scales in southern Africa. *Ecological Applications*, **24**, 1188-1203. CrossRef

Hanke, W., Gröngröft, A., Jürgens, N. & Schmiedel, U. (2011) Rehabilitation of arid rangelands: Intensifying water pulses from low-intensity winter rainfall. Journal Of of Arid Environments, **75**, 185-193. CrossRef

Hauptfleisch, M., Vinte, M. & Blaum, N. (2017) A comparison of the community dynamics of bioturbating small mammals between livestock and wildlife farming areas in the Kalahari, Namibia. *Namibian Journal of Environment; Vol 1 (2017): Namibian Journal of Environment*.

Hillmann, T., Muche, G., Josenhans, K. & Jürgens, N. (2018) Online presentation of the SASSCAL ObservationNet. This Volume. CrossRef

Hudson, L.N., Newbold, T., Contu, S. et al. (2017) The database of the PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) project. Ecology and Evolution, **7**, 145-188. CrossRef

Huete, A.R. (1988) A Soil-Adjusted Vegetation Index (SAVI). *Remote Sensing of Environment*, **25**, 295–309. CrossRef

Huete, A.R., Hua, G., Qi, J.C. & van Leeuwen, W.J.D. (1992) Normalization of Multidirectional Red and NIR Reflectances with the SAVI. *Remote Sensing of Environment*, **41**, 143–154. CrossRef

Huntley, B. & Matos, E. (1994) Botanical diversity and its conservation in Angola. *Strelitzia* **1**, 53-74.

Jacke, V. (2016) *Vegetation patterns in space and time on long-term observation plots in the South African Kalahari.* MSc. thesis, University of Hamburg, Hamburg.

Jürgens, N. (2006) Recent change of flora and vegetation in Namibia – a brief review of dynamics drivers and scientific approaches. In: Leser, H. (Ed.), The Changing Culture and Nature of Namibia: Case Studies. The Sixth Namibia Workshop, in Honour of Dr. h. c. Carl Schlettwein (1925–2005), Basel 2005. Basler Afrika Bibliographien, Basel, pp. 91–108. CrossRef

Jürgens, N., Gotzmann, I.H. & Cowling, R.M. (1999) Remarkable medium-term dynamics of leaf succulent Mesembryanthemaceae shrubs in the winter-rainfall desert of northwestern Namaqualand, South Africa. *Plant Ecology*, **142**, 87-96. CrossRef

Jürgens, N., Haarmeyer, D.H., Luther-Mosebach, J., Dengler, J., Finckh, M. & Schmiedel, U. eds. (2010) *Patterns at Local Scale: The BIOTA Observatories*, Klaus Hess Publishers, Göttingen & Windhoek.

Jürgens, N., Oldeland, J., Hachfeld, B., Erb, E. & Schultz, C. (2013) Ecology and spatial patterns of large-scale vegetation units within the central Namib Desert. *Journal of Arid Environments*, **93**, 59–79. CrossRef

Jürgens, N., Schmiedel, U., Haarmeyer, D.H. et al (2012) The BIOTA Biodiversity Observatories in Africa--a standardized framework for large-scale environmental monitoring. *Environmental monitoring and assessment*, 184, 655–78. CrossRef

Klintenberg P, Seely M. (2004) Land degradation monitoring in Namibia: a first approximation. *Environmental Monitoring and Assessment*, **99**, 5-21. CrossRef

Mbata, K.J. (2018) Annotated checklist of cockroaches and termites of Zambia (Arthropoda: Insecta; Blattodea). This volume. CrossRef

Mendelsohn JM, vanderPost C, Ramberg L, Murray-Hudson M, Wolski P & Mosepele K. 2010. Okavango Delta: Floods of Life. RAISON, Windhoek, 1-144.

Meyer, G.E. & Neto, J.C. (2008) Verification of color vegetation indices for automated crop imaging applications. *Computers and Electronics in Agriculture*, **63**, 282–293. CrossRef

Mucina, L. & Rutherford, M.C. eds. (2006) *The Vegetation of South Africa, Lesotho and Swaziland*, South African National Biodiversity Institute, Pretoria.

Mucina, L., Jürgens, N., Le Roux, A., Rutherford, M.C., Schmiedel, U., Esler, K.J., Powrie, L.W., Desmet, P.G. & Milton, S.J. (2006) Succulent Karoo Biome. The vegetation of South Africa, Lesotho and Swaziland (ed. by L. Mucina and M.C. Rutherford), pp. 221-229. South African National Biodiversity Institute Pretoria.

Oldeland, J., Große-Stoltenberg, A., Naftal, L. & Strohbach, B.J. (2017) *The potential of UAV derived image features for discriminating savannah tree species. The Roles of Remote Sensing in Nature Conservation* (ed. by R. Díaz-Delgado), R. Lucas), and C. Hurford), pp. 183–201. Springer International Publishing. CrossRef

Pole Evans, I.B. (1948) A reconnaissance trip through the eastern portion of the Betchuanaland Protectorate and an expedition to Ngamiland. *Botanical Survey of South Africa*, **21**, 1–73.

Proença, V., Martin, L.J., Pereira, H.M., Fernandez, M., McRae, L., Belnap, J., Böhm, M., Brummitt, N., García-Moreno, J., Gregory, R.D., Honrado, J.P., Jürgens, N., Opige, M., Schmeller, D.S., Tiago, P. & van Swaay, C.A.M. (2016) Global biodiversity monitoring: From data sources to Essential Biodiversity Variables. *Biological Conservation*, **213**, 256-263. CrossRef

Rasmussen, J., Ntakos, G., Nielsen, J., Svensgaard, J., Poulsen, R.N. & Christensen, S. (2016) Are vegetation indices derived from consumer-grade cameras mounted on UAVs sufficiently reliable for assessing experimental plots? *European Journal of Agronomy*, **74**, 75–92. CrossRef

Raunkiaer, C. (1937) *Plant life forms*, The Clarendon Press, Oxford.

Rodgers, M., Bilton, M. & Hauptfleisch, M. (2017) Responses and feedbacks of burrowing mammals under differently managed rangelands. *Namibian Journal of*

Environment; Vol 1 (2017): Namibian Journal of Environment.

Schmiedel, U., Araya, Y., Bortolotto, M.I., Boeckenhoff, L., Hallwachs, W., Janzen, D., Kolipaka, S.S., Novotny, V., Palm, M., Parfondry, M., Smanis, A. & Toko, P. (2016) Contributions of paraecologists and parataxonomists to research, conservation, and social development. *Conservation Biology*, **30**, 506-519. CrossRef

Schmiedel, U., Dengler, J. & Etzold, S. (2012) Vegetation dynamics of endemic-rich quartz fields in the Succulent Karoo, South Africa, in response to recent climatic trends. *Journal of Vegetation Science*, **23**, 292–303. CrossRef

Schmiedel, U., Dengler, J., Luther-Mosebach, J., Gröngröft, A., Muche, G., Petersen, A., Strohbach, B.J. and Jürgens, N. (2010) Patterns and dynamics of vascular plant diversity along the BIOTA transects in southern Africa. In *Biodiversity in southern Africa*, 2, (ed. by Schmiedel, U, & Jürgens, N.) pp.118-135. Klaus Hess Publishers, Göttingen and Windhoek.

Shidolo, E.L.K. (2017) Assessment of vegetation diversity, structure, cover and the influence of fire along the rainfall gradient in the Kalahari, East of Namibia, using long-term data. Masters in Natural Resources Management thesis, Namibia University of Science and Technology.

Strohbach, B. (2017a) Experiences with the eBee Drone Part 1. *SASSCAL News*, **2**, 17–20.

Strohbach, B. (2017b) Experiences with the eBee Drone Part 2. *SASSCAL News*, **2**, 20–23.

Strohbach, B.J. & Hauptfleisch, M.L. (submitted) Rehabilitation success at the Oshikoto Mine, Otjiozondjupa Region in Namibia, as determined with high-resolution NIR aerial imagery. *Namibia Journal of Environment*.

Strohbach, B.J. (2013) Vegetation of the Okavango River valley in Kavango West, Namibia. *Biodiversity & Ecology*, **5**, 321–339. CrossRef

Strohbach, B.J. (2014) Vegetation of the Eastern Communal Conservancies in Namibia: I. Phytosociological descriptions. *Koedoe - African Protected Area Conservation and Science*, **56**.

Strohbach, B.J. (2017c) Making more of vegetation classification results: A Livestock Farming Suitability Index as tool for Land-Use Planning in Namibia. *Phytocoenologia*.

Strohbach, B.J. (2017d) Vegetation of the Auas-Oanob Conservancy in the Khomas Hochland of Namibia. *Namibian Journal of Environment*, **1**.

Tshireletso, K., Makhabu, S.W., Nsinamwa, M., Kgosiesele, E., Setlalekgomo, M.R., Seletlo, Z., Majaga, S., & Legwatagwata, B. (2018) Diversity patterns of woody vegetation of Kgatleng District, Botswana. This volume. CrossRef

Van Wilgen, B.W., Govender, N. and Biggs, H.C. (2007) The contribution of fire research to fire management: a critical review of a long-term experiment in the Kruger National Park, South Africa. *International Journal of Wildland Fire*, **16**, 519-530. CrossRef

Verlinden A., Laamanen R. (2006) Long term fire scar monitoring with remote sensing in Northern Namibia: relations between fire frequency, rainfall, land cover, fire management and trees. *Environmental Monitoring and Assessment*, **112**,231-53. CrossRef

Walters, M.H. (2016) Determining the changes in vegetation structure in three semi-arid savanna environments in Namibia over the past 60 years. Bachelor Honours in Natural Resources Management mini-thesis, Namibia University of Science and Technology.

Western, D. & Vigne, L. (1985) The deteriorating status of African rhinos. *Oryx*, **19**, 215. CrossRef

White, F. (1983) *The Vegetation of Africa – A descriptive memoir to accompany the Unesco/AETFAT/UNSO vegetation map of Africa*. United Nations Educational Scientific and Cultural Organisation, Paris. 356 pp.

Wolski, P., Murray-Hudson, M., Thito, K. & Cassidy, L. (2017) Keeping it simple: Monitoring flood extent in large data-poor wetlands using MODIS SWIR data. *International Journal of Applied Earth Observation and Geoinformation*, **57**, 224-234. CrossRef

Amphibians and reptiles of the Tundavala region of the Angolan Escarpment

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Biodiversity

Abstract: The most poorly known section of the African Great Escarpment is located in Angola. It has been highlighted as a potential center of endemism for several biological groups, including herpetofauna. The region, which is critical for the conservation of Angolan biodiversity, requires urgent research. In the scope of the SASSCAL project, a herpetofauna monitoring plan is being implemented in Tundavala, in the southern Angolan escarpment. In total, 13 species of amphibians, 12 species of lizards and 9 species of snakes have been registered so far, and more are expected to occur. Among them are some important rediscoveries of Angolan endemics uncollected for decades, such as Anchieta's treefrog (*Leptopelis anchietae*) and Ansorge's whip snake (*Psammophis ansorgii*).

Resumo: A secção menos conhecida da Grande Escarpa Africana localiza-se em Angola. Esta já foi destacada como um potencial centro de endemismo para vários grupos, incluindo a herpetofauna, sendo por isso uma região crítica para a conservação da biodiversidade angolana que carece urgentemente de investigação. No âmbito do projecto SASSCAL, está a ser implementado um plano de monitorização de herpetofauna na Tundavala, no sul da escarpa de Angola. Até ao momento foram registadas 13 espécies de anfíbios, 12 espécies de lagartos e nove espécies de cobras, e presume-se que existam mais. Entre estas, estão redescobertas importantes de endemismos angolanos não registados há várias décadas, como a rã-arborícola-de-Anchieta (*Leptopelis anchietae*), e a cobra-de-Ansorge (*Psammophis ansorgii*).

Introduction

The Angolan section is the most poorly known of the African Great Escarpment, and yet it supports the highest number of vertebrate endemics after those in South Africa (Clark et al., 2011). It is rich in endemic plants and birds and is a potential hotspot for Angolan biodiversity (Hall, 1960). However, more research is required to identify and meaningfully implement conservation objectives, especially detailed biodiversity surveys and systematic studies. These will allow the effects of predicted climate change, highlighted by Clark et al. (2011), to be identified, and refugia and migration hypotheses to be formulated and tested.

Tundavala is located on the Angolan escarpment in southwestern Angola (Fig. 1), and its outstanding landscape makes it one of the most important tourist destinations in the country. The creation of a nature reserve in Tundavala was proposed by Huntley & Matos (1994), and the reserve is mentioned in the Angolan National Biodiversity Strategy and Action Plan (NBSAP, 2006) as a protected area to be implemented. It is also classified as an Important Bird Area (BirdLife International, 2017), and the Tundavala Crevice was classified as a Cultural Landscape in 2012 (Executive decree no. 261/12). Despite its social and biological importance, the region lacks official national protected status and is threatened by progressively increasing human activities, especially logging and burning for charcoal production and the harvesting of natural resources such as medicinal plants and rocks for building purposes. Increasing numbers of villagers inhabit the region with their livestock (cows and goats) and plant crops. Other threats include man-made fires and the dumping of rubble and domestic, commercial, and even medical waste.

Southwestern Angola is one of the better-surveyed regions of Angola for all vertebrate groups (Crawford-Cabral & Mesquitela, 1989), and the herpetofauna is no exception, with numerous studies addressing it (Bocage, 1895; Schmidt, 1933, 1936; Parker, 1936; Monard, 1937a,b; Mertens, 1938; Bogert, 1940; Loveridge, 1944; Hellmich, 1957; FitzSimons, 1959; Laurent, 1964; Poynton & Haacke, 1993; Haacke, 1997). Despite this, new species continue to be described from the region (Haacke, 2008; Conradie et al., 2012; Stanley et al., 2016). Little work has focused specifically on the escarpment region, and its herpetofauna is

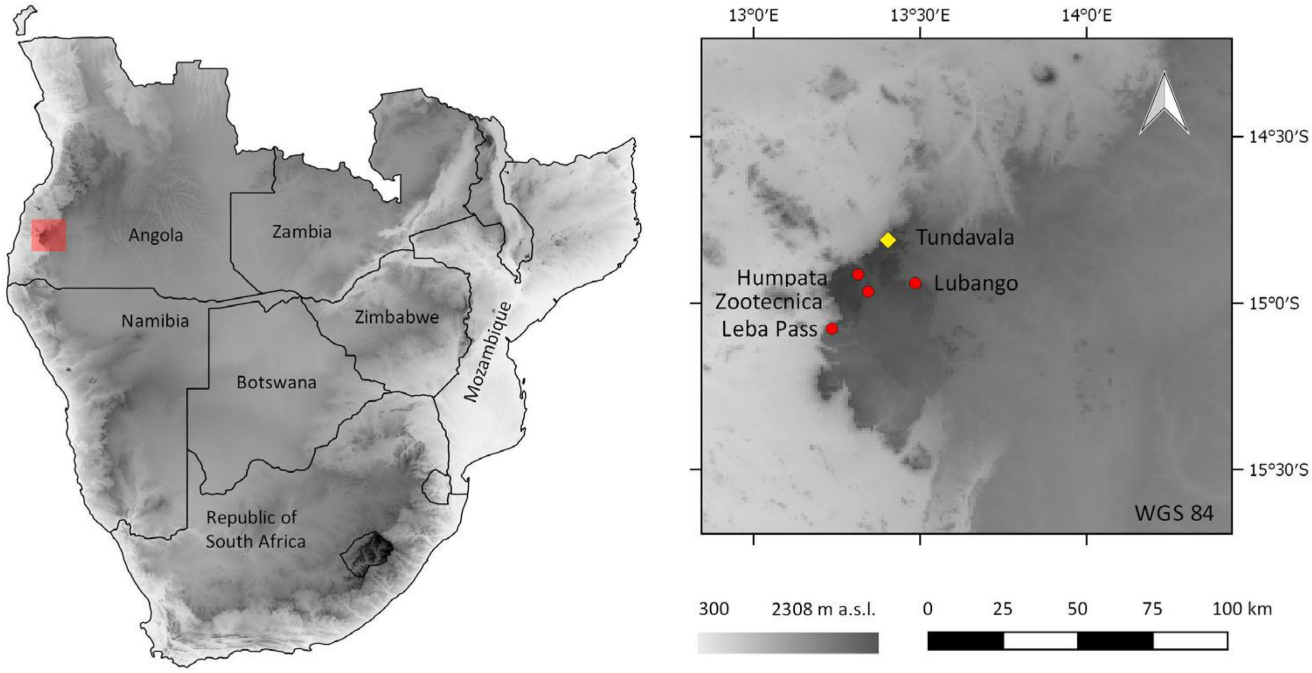

Figure 1: Left: Location of the study site in the African Great Escarpment. Right: Localities near the study area mentioned where additional species expected in Tundavala were recorded.

far from being completely understood. The Humpata Plateau, including Tundavala, has been identified as a potential center of endemism for montane herpetofauna and is therefore a priority area for herpetofaunal surveys (Laurent, 1964).

The main goal of the SASSCAL Project's observatories (task 210) is to monitor biodiversity to understand the effects of climate change and land use on plant communities in the long term. Several observatories have been implemented throughout Angola, including one in Tundavala. The herpetofauna is frequently cited as a useful indicator for environmental monitoring thanks to its importance in ecological functioning and its sensitivity to environmental change (Smith & Rissler, 2010). In this context, a monitoring program of the Tundavala herpetofauna was initiated in 2016. The compilation of baseline information, such as presence and absence of species and their relative abundances in the mid- and long term, is essential for the effective management of this critical region for the conservation of Angolan biodiversity. This is the first herpetofauna monitoring plan implemented in Angola. The project is ongoing, and preliminary and more relevant findings are presented in this publication.

Figure 2: Montane grassland (grassy habitat) at first monitoring site.

Figure 3: Weathered sandstone outcrops (rocky habitat) and associated woody and grassy vegetation at second monitoring site.

Common name	Species	Family
Anchieta's Treefrog	(E) *Leptopelis anchietae* (Bocage, 1873)	Arthroleptidae
Bocage's Treefrog	*Leptopelis* cf. *bocagii* (Günther, 1865)	Arthroleptidae
Guttural Toad	*Sclerophrys* cf. *gutturalis* (Power, 1927)	Bufonidae
Flat-Backed Toad	*Sclerophrys* cf. *pusilla* (Mertens, 1937)	Bufonidae
Monard's Reed Frog	(E) *Hyperolius cinereus* Monard, 1937	Hyperoliidae
Angola Reed Frog	*Hyperolius* cf. *parallelus* Günther, 1858	Hyperoliidae
Benguela Long Reed Frog	*Hyperolius* cf. *benguellensis* (Bocage, 1893)	Hyperoliidae
Bubbling Kassina	*Kassina senegalensis* (Duméril and Bibron, 1841)	Hyperoliidae
Mababe Puddle Frog	*Phrynobatrachus* cf. *mababiensis* FitzSimons, 1932	Phrynobatrachidae
Peters' Clawed Frog	*Xenopus* cf. *petersii* Bocage, 1895	Pipidae
Anchieta's Ridged Frog	*Ptychadena* cf. *anchietae* (Bocage, 1868)	Ptychadenidae
Angola River Frog	*Amietia angolensis* (Bocage, 1866)	Pyxicephalidae
Rough Sand Frog	*Tomopterna* cf. *tuberculosa* (Boulenger, 1882)	Pyxicephalidae

Table 1: Amphibian species recorded from the Tundavala observatory and close surroundings. (E) indicates species endemic to the Angolan highlands.

Common name	Species	Family
	Lizards (Sauria)	
Ground Agama	*Agama* cf. *aculeata* (Merrem, 1820)	Agamidae
Namib Rock Agama	*Agama* cf. *planiceps* Peters, 1862	Agamidae
Double-scaled Chameleon	*Chamaeleo anchietae* Bocage, 1872	Chamaeleonidae
Machado's Girdled Lizard	(E) *Cordylus machadoi* Laurent, 1964	Cordylidae
Speckled Thick-toed Gecko	*Pachydactylus* cf. *punctatus* Peters, 1854	Gekkonidae
Montane Day Gecko	(E) * *Rhoptropus boultoni montanus* Laurent, 1964	Gekkonidae
Western Serpentiform Skink	*Eumecia anchietae* Bocage, 1870	Scincidae
Angola burrowing Skink	*Sepsina* cf. *angolensis* Bocage, 1866	Scincidae
Hoesch's skink	*Trachylepis hoeschi* (Mertens, 1954)	Scincidae
Western Rock Skink	(E) * *Trachylepis sulcata ansorgei* (Boulenger, 1907)	Scincidae
Variable Skink	*Trachylepis* cf. *varia* (Peters, 1867)	Scincidae
Wahlberg's Skink	*Trachylepis wahlbergi* (Peters, 1869)	Scincidae
	Snakes (Serpentes)	
Angolan Green Snake	*Philothamnus angolensis* (Bocage, 1882)	Colubridae
Confusing Egg-Eater	*Dasypelis* cf. *confusa* (Trape & Mané, 2006)	Colubridae
Anchieta's cobra	*Naja anchietae* Bocage, 1879	Elapidae
Viperine Rock Snake	*Hemirhagerrhis viperina* (Bocage, 1873)	Lamprophiidae
Spotted Wolf Snake	*Lycophidion* cf. *multimaculatum* Boettger, 1888	Lamprophiidae
Ansorge's Whip Snake	(E) *Psammophis ansorgii* (Boulenger, 1905)	Lamprophiidae
Mozambique Grass Snake	*Psammophis* cf. *mossambicus* (Peters, 1882)	Lamprophiidae
Ocellated Skaapsteker	(E) *Psammophylax rhombeatus ocellatus* (Bocage, 1873)	Lamprophiidae
Blind Snake	*Afrotyphlops* cf. *anomalus* (Bocage, 1873)	Typhlopidae

Table 2: Reptile species recorded from the Tundavala observatory and close surroundings. (E) indicates species endemic to the Angolan highlands. (*) indicates cases where taxonomy follows Laurent (1964).

Methods

Survey area

The Tundavala region of the plateau is composed of a mosaic of vegetation types and rugged topography. Patches of relict Afromontane forest with *Podocarpus milanjianus* occur in deep humid ravines and at altitudes above 1,800 m (Huntley & Matos, 1994). They co-occur on the escarpment plateau with patches of open *Protea* savanna, *Pteridium* bracken, miombo woodlands on sands, montane grasslands, thickets along seasonal streams, and poorly drained grassy patches in valleys (BirdLife International, 2017), and provide diverse habitats for the herpetofauna.

Monitoring

Herpetofauna monitoring in the SASSCAL Tundavala observatory region involved standardized sampling in the two habitat types occurring in the observatory area: sandy soils with montane grassland (grassy habitat, Figure 2), and "corridors" of undifferentiated woody montane communities between large weathered sandstone outcrops (rocky habitat, Figure 3). Preliminary herpetological surveys began in November 2015. Standardized monitoring was initiated in April 2016, with three monitoring sessions each year: following early rains (October–November), at the peak of the rainy season (February), and at the end of the rainy season (late April). Monitoring involves the installation of two 15-meter-long traplines, each associated with six funnel and two pit fall traps. These are placed for 14 consecutive days and are checked daily. In addition, 20 time-constrained transects with visual encounter surveys (VES) are done on sunny mornings (10) and afternoons (10). Both techniques are undertaken equally in grassy and rocky habitats. Additional VESs are undertaken opportunistically in unmonitored habitats during day and night, as are auditory surveys for adult frogs and tadpole sampling. Small mammals are also included in the Tundavala monitoring plan, but results are not addressed in the present work.

Reptiles and amphibians were collected and deposited in the herpetological collection currently deposited at the Instituto Superior de Ciências da Educação da Huíla (ISCED-Huíla), and tissue for genetic analysis has been preserved in 95% ethanol for use in ongoing and further research. Preliminary identification of species is based on Channing (2001, 2012) and Branch (1998), supplemented with taxa-specific literature when needed. Taxonomy follows Frost (2017) for amphibians and Uetz & Hošek (2017) for reptiles, except where noted. All pictures of landscape and animals are from Tundavala.

Results

Sampling success

Trapping success of herpetofauna at Tundavala has been low, regardless of the sampling season. In the four sampling seasons performed, fewer than 15 individuals were caught in the traplines, and in one sampling season in particular, only one individual was captured during the 14 days of sampling. As a result of low catch rates at Tundavala, the data do not allow in-depth or temporal analysis, and thus we will focus on the observed herpetofaunal diversity and its biogeographic importance.

Species list

A total of 13 species of frogs (Tab. 1), 12 species of lizards, and 9 species of snakes (Tab. 2) were recorded during the monitoring and opportunistic surveys in the observatory and close surroundings.

Most species were caught too few times to establish habitat associations. Some reptile species were regularly associated with rocky habitats (e.g., *Agama* cf. *planiceps*, *Rhoptropus b. montanus*, and *Hemirhagerrhis viperina*), whilst others were found in both habitats (e.g., *Psammophylax r. ocellatus*). As expected, most amphibians except *Sclerophrys* spp., *Tomopterna tuberculosa*, and *Leptopelis bocagii* were found only near water bodies.

Additional species recorded from Lubango and adjacent regions of the escarpment may be expected to occur in Tundavala given their habitat associations, but have not been recorded so far. Among these, some have been found in Humpata: snout burrower, *Hemisus* sp. (Branch et al., unpub. Data); long-headed tropical house gecko, *Hemidactylus longicephalus* Bocage, 1873; Angolan rough-scaled lizard, *Ichnotropis bivittata pallida* Laurent, 1964; Bayon's skink, *Trachylepis bayonii huilensis* (Laurent, 1964)*; Angolan garter snake, *Elapsoidea semiannulata* Bocage, 1882) (all records from Laurent, 1964). Others have been recorded in Lubango: African house snake, *Boaedon* cf. *fuliginosus* (Boie, 1827); leopard grass snake, *Psammophis leopardinus* Bocage, 1887; three-lined grass snake, *Psammophylax tritaeniatus* (Günther, 1868) (Vaz Pinto, pers. obs.), and in Lubango, Leba Pass, and the Estação Zootécnica: flap-necked chamaeleon, *Chamaeleo dilepis* (Leach, 1819) (Brach et al., unpub. data; Baptista, pers. obs.); flat gecko *Afroedura* sp., snake-eyed skink *Panaspis* sp. (Vaz Pinto & Baptista, *unpub. data*), and the endemic habitat specialist Chela reed frog, *Hyperolius chelaensis* (Conradie et al., 2012).

Discussion

Monitoring success

The herpetological monitoring program in the Tundavala observatory region has been of only limited success and requires adjustment. New approaches considered include surveys at different times during the day, checking traplines twice daily, and modifying the trapline arrangement to use a Y-shaped (3 arms of 15 m) array in grassy areas. Opportunistic acoustic surveys and tadpole collection proved productive and will be standardized and included in the monitoring plan on a systematic basis.

The Tundavala plateau has varied soils, geology, topography, and vegetation types that provide different habitats and microhabitats for the herpetofauna. Currently, systematic monitoring covers only two habitat types and therefore does not fully survey the entire herpetofaunal diversity of the plateau and the escarpment.

Species list, taxonomy, and conservation relevance

Many of the species listed in Tables 1 and 2 have been only provisionally identified. This reflects the current poor state of knowledge of the Angolan herpetofauna. Many of the provisional identifications involve wide-ranging species or species complexes in which cryptic diversity has recently been identified but for which no, or little, Angolan material was included. Other species are poorly known Angolan species, some known from very few specimens and for which the types were lost in the fire that destroyed the Lisbon Museum in 1978. These problematic species, of which some may be new to science, given the geographic setting of Tundavala, are either currently under investigation or will require further investigation when additional, often topotypic material becomes available. Taxonomic issues associated with some of these species are addressed below.

Figure 4: Anchieta's treefrog (*Leptopelis anchietae*), breeding male.

Leptopelis anchietae (Bocage, 1873)

This species is known from Missão da Huíla, Caconda, and Quindumbo (Bocage, 1895); "between Benguela and Bié" (Boulenger, 1905); Caluquembe, Ebanga, Missão do Cubango (Monard, 1937a); Chitau (Schmidt, 1936); and Alto Chicapa (Laurent, 1964). It is endemic to the Angolan plateau (Monard, 1937a). The specimens from Tundavala (Fig. 4) correspond in morphology and coloration with the type description and plate in Bocage (1895). Details of this rediscovery and those of other *Leptopelis* from northern areas of the Angolan escarpment will be presented elsewhere (Baptista et al., in prep.).

Leptopelis* cf. *bocagii (Günther, 1865)
This species, originally described from Calandula (formerly Duque de Bragança), is considered widespread in Africa, including the north, west, and south of Angola (Bocage, 1895; Ferreira, 1904, 1906; Schmidt, 1936; Monard, 1937a; Laurent, 1954, 1964; Hellmich, 1957; Laurent, 1954, 1964). It is thought to be a complex of cryptic species (Frost, 2017), and the availability of Angolan material on *Hylambates angolensis* Bocage, 1893, currently in the synonymy of *L. bocagii*, needs further study (Perret, 1967).

Sclerophrys spp.
The status of the Angolan toad taxonomy needs to be readdressed (Ruas, 1996). *S. gutturalis* is widespread in the country, and the recently renamed *Sclerophrys pusilla* (Poynton et al., 2016) is known mostly from western Angola (Ruas, 1996). However, both species have wide distributions in Africa, and their taxonomy and the availability of names for Angolan material still requires further investigation..

Hyperolius cinereus Monard, 1937
An endemic from the Angolan plateau, historically known from only a few localities, this species' distribution has been found to be much more widespread (Conradie et al., 2016).

Figure 5: Angolan reed frog (*Hyperolius* cf. *parallelus*), breeding male.

Hyperolius* cf. *parallelus (Günther, 1858) and ***Hyperolius* cf. *benguellensis*** (Bocage, 1893)
Both these species consist of "super complexes" in Africa. *H. parallelus* is closely related to the problematic *H. marmoratus*, and *H.* cf. *benguellensis* belongs to the equally unresolved *H. nasutus* complex, which has recently been revised (Channing et al., 2013). Both species are widespread in Angola and have several names in their synonymy, with variations in shape, size, and coloration. Comprehensive studies, including wide geographical surveys combined with genetics and advertisement calls, are needed to resolve the taxonomy of both groups. An Angolan reed frog from Tundavala is shown in Figure 5.

Tomopterna* cf. *tuberculosa (Boulenger, 1882)
One of the most common species of frog in the monitoring region, with a variety of color morphs. Originally described from Pungo Andongo on the Angolan central plateau, this species is widespread in the country (Ruas, 1996), extends east to central coastal Mozambique, and may comprise a complex of cryptic species. Other available names for Angolan material currently subsumed under *T. tuberculosa* include *Rana cacondana* and *Rana signata*. Advertisement calls and genetics are crucial to resolving these issues.

Figure 6: Ocellated skaapsteker (*Psammophylax rhombeatus ocellatus*).

Psammophylax rhombeatus ocellatus (Bocage, 1873)
This taxon has morphological differences (Fig. 6) and is separated from the typical race in South Africa, with a few scattered records in northern Namibia (Kamanjab [Broadley, 1977]; Kaross [Hoffman, 1989]). Its status as a full species is currently being investigated (Branch et al., in prep.).

Psammophis ansorgii (Boulenger, 1905)
This snake is very poorly known. The type locality of the single type is vague ("Benguela to Bihe, Angola"), and the only subsequent material comprises six heads and one body from Bella-Vista (Hellmich, 1957). The Tundavala specimens (Fig. 7) are the first with detailed locality and habitat. They agree morphologically with the description and the plate provided in the original description (Boulenger, 1905), and its phylogenetic affinities within *Psammophis* are currently being addressed (Branch et al., in prep.).

Figure 7: Ansorge's whip snake (*Psammophis ansorgii*).

Eumecia anchietae Bocage, 1870
This serpentiform skink was described from "Huilla Plateau" (Bocage, 1870), and the Tundavala material can therefore be considered topotypic material and the first collected since the type description. The species has a curiously disjunct distribution, with isolated populations known from the Upemba Plateau, DRC, NW Zambia, northern Serengeti, etc. Various subspecies have been proposed (Laurent, 1964) but have never been reassessed within a modern, integrated taxonomic framework. Whether the species is a complex of cryptic, vicariant species remains unresolved and is the subject of ongoing research (Branch et al., in prep.).

Chamaeleo anchietae Bocage, 1872
Double-scaled chameleons from Tundavala (Fig. 8) correspond morphologically to

Figure 8: Double-scaled chameleon (*Chamaeleo anchietae*).

the original description (Bocage, 1872). As with *Eumecia anchietae,* this taxon was described from "Huilla" (Bocage, 1872) and also has similarly disjunct distribution (i.e., Marunga Plateau, Katanga, Kivu, DRC; Udzungwa Mountains, Tanzania). Various subspecies have been proposed (Laurent, 1952), but their status remains unresolved (possibly comprising a complex of cryptic, vicariant species) and is the subject of ongoing research (Branch et al., in prep.).

Trachylepis hoeschi (Mertens, 1954)
This fat terrestrial skink was found in montane grasslands, often near termite mounds in which it may shelter. It is endemic to Angola and Namibia, and previously known in Angola only from lowlands in Namibe province (Laurent, 1964; Haacke *unpub. data*; Branch *unpub. data*; Ceríaco *et al.*, 2016). This record constitutes an important range extension of the species onto the plateau, above 2200 m a.s.l.. Further studies will help reveal if the species is tolerant to altitudinal range, or if the upland population reflects cryptic speciation.

Figure 9: Hoesch's skink (*Trachylepis hoeschi*).

Although the Angolan escarpment has affinities with the adjoining biomes, it acts as a barrier between the drier coastal plains and the inland plateaus, allowing speciation to develop (Huntley, 1974), explaining the high level of endemism observed in the region (see Tab. 1 and Tab. 2). At least five of the recorded species consist of important rediscoveries of Angolan plateau endemics. *Psammophis ansorgii* and *Leptopelis anchietae* have not been recorded for 60 and 53 years, respectively, which is not a total surprise, given the lack of studies in Angola for decades as a consequence of the civil war and lack of zoologists. The specimens of *Psammophylax rhombeatus ocellatus, Chamaeleo anchietae,* and *Eumecia anchietae,* recorded recently (this study and Branch et al., unpub. data, and Vaz Pinto, pers. comm.), are the first for many decades in Angola. The type specimens for all of the species described by Bocage, were lost in the 1978 fire that burnt the Lisbon Museum, and thus the rediscovery of these species is critical for taxonomic studies and may facilitate the nomination of neotypes and the resolution of cryptic diversity within disjunct populations.

Conservation

The presence of a high number of endemic amphibians and reptiles in the Tundavala region, though the taxonomic status of many species remains unresolved, highlights the relevance and urgency of effective protection of the region. Further studies on the recorded species may reveal further cryptic diversity and thus amplify further the urgency for its protection. More comprehensive surveys in adjacent habitats will also likely increase the number of species recorded in the region.

In many respects, Tundavala represents only the tip of the iceberg when it comes to the immense and poorly known herpetological diversity of the Angolan escarpment. As Clark et al. (2011) have highlighted, further research and conservation are urgently needed. The study of the biogeography and herpetofauna of the rest of the Angolan escarpment is of high priority. Herpetological surveys in northern regions of the escarpment, such as Kwanza Sul and Kwanza Norte, have taken place and will be continued (Baptista et al., in prep.).

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References

BirdLife International (2017) Important Bird Areas factsheet: Tundavala. Downloaded from http://www.birdlife.org on 28 June 2017.

Bocage, J.V.B. (1870) Description d'un "Saurien" nouveau de l'Afrique occidentale. *Jornal de Sciencias Mathematicas, Physicas e Naturaes*, **3**, 66–68.

Bocage, J.V.B. (1872) Diagnoses de quelques espéces nouvelles de Reptiles d'Afrique occidentale. *Jornal de Sciencias Mathematicas, Physicas e Naturaes*, **4**, 72–82.

Bocage, J.V.B. (1895) *Herpétologie d'Angola et du Congo*. Ministério da Marinha e das Colónias, Lisbon.

Bogert, C.M. (1940) Herpetological results of the Vernay Angola Expedition with notes on African reptiles in other collections. Part 1, Snakes, including an arrangement of African Colubridae. *Bulletin of the American Museum of Natural History*, **77**, 1–107.

Boulenger, G.A. (1905) A list of the batrachians and reptiles collected by Dr. W.J. Ansorge in Angola, with descriptions of new species. *Annals and Magazine of Natural History*, ser. 7, **16**, 8–115.

Branch, W.R. (1998) *Field guide to snakes and other reptiles of southern Africa*. Struik. Cape Town.

Broadley, D.G. (1977) A revision of the African snake genus *Psammophylax* Fitz Ingersoll (Colubridae). *Arnoldia (Rhodesia)*, **8**, 1–44.

Channing, A. (2001) *Amphibians of central and southern Africa*. Comstock Pub. Associates. Cornell University Press. New York.

Channing, A., Rödel, M.O. & Channing, J. (2012) *Tadpoles of Africa: The biology and identification of all known tadpoles in sub-Saharan Africa*. Edition Chimaira, Frankfurt.

Channing, A., Hillers, A., Lötters, S., Rödel, M.O., Schick, S., Conradie, W., Rödder, D., Mercurio, V., Wagner, P., Dehling, J.M., Du Preez, L.H., Kielgast, J. & Burger, M. (2013) Taxonomy of the super-cryptic *Hyperolius nasutus* group of long reed frogs of Africa (Anura: Hyperoliidae), with descriptions of six new species. *Zootaxa*, ***3620***, 301–350.

Clark, V.R., Barker, N.P. & Mucina, L. (2011) The Great Escarpment of southern Africa: a new frontier for biodiversity exploration. *Biodiversity and Conservation*, **20**, 2543–2561.

Conradie, W., Bills, R. & Branch, W.R. (2016) The herpetofauna of the Cubango, Cuito, and lower Cuando river catchments of south-eastern Angola. *Amphibian & Reptile Conservation*, **10**, 6–36.

Conradie, W., Branch, W.R., Measey, G.J. & Tolley, K.A. (2012) A new species of *Hyperolius* Rapp, 1842 (Anura: Hyperoliidae) from the Serra da Chela mountains, south-western Angola. *Zootaxa*, **3269**, 1–17.

Crawford-Cabral, J. & Mesquitela, L.M. (1989) Índice toponímico de colheitas zoológicas em Angola (Mammalia, Aves, Reptilia e Amphibia). *Estudos, ensaios e documentos.* Instituto de Investigação Científica Tropical,Lisboa, 206 pp.

Ferreira, J.B. (1904) Reptis e amphibios de Angola da região ao norte do Quanza (Collecção Newton – 1903). *Jornal de Sciencias Mathematicas, Physicas e Naturaes, Segunda Série,* **7**, 111–117.

Ferreira, J.B. (1906) Algumas espécies novas ou pouco conhecidas de amphibios e reptis de Angola (Collecção Newton – 1903–1904). *Jornal de Sciencias Mathematicas, Physicas e Naturaes, Segunda Série,* **7**, 159–171.

FitzSimons, V. (1959) Some new reptiles from southern Africa and southern Angola. *Annals of the Transvaal Museum,* **23**, 405–409.

Frost, Darrel R. (2017) Amphibian species of the world: an online reference, version 6.0 (28 June 2017). American Museum of Natural History, New York, USA. Electronic database accessible at http://research.amnh.org/herpetology/amphibia/index.html

Haacke, W. (1997) Systematics and biogeography of the southern African scincine genus *Typhlacontias* (Reptilia: Scincidae). *Bonner zoologische Beitrage*, **47**, 139–164.

Haacke, W.D. (2008) A new leaf-toed gecko (Reptilia: Gekkonidae) from south-western Angola. *African Journal of Herpetology*, **57**, 85–92.

Hall, B.P. (1960) The faunistic importance of the scarp of Angola. *Ibis*, **102**, 420–442.

Hellmich, W. (1957) Herpetologische Ergebnisse einer Forschungsreise in Angola. *Veröffentlichungen der Zoologischen Staatssammlung München*, **5**, 1–92.

Hoffman, L.A.C. (1989) An annotated list of amphibian and reptile observations from the Etosha National Park. *Madoqua*, **16**, 87–92.

Huntley, B.J. (1974) Outlines of wildlife conservation in Angola. *South African Journal of Wildlife*, **4**, 157–166.

Huntley, B.J. & Matos, E.M. (1994) Botanical diversity and its conservation in Angola. *Strelitzia*, **1**, 53–74.

Laurent, R.F. (1952) Reptiles et batraciens nouveaux du massif du mont Kabobo et du plateau des Marungu. *Revue de Zoologie et de Botanique Africaines,* **46**, 18–34.

Laurent, R.F. (1954) Reptiles et batraciens de la région de Dundo (Angola) (Deuxième note). *Publicações Culturais da Companhia de Diamantes de Angola*, **23**, 35–84.

Laurent, R.F. (1964) Reptiles et amphibiens de l'Angola (Troisème contribution). *Publicações Culturais. Companhia de Diamantes de Angola, Lisboa,* **67**, 1–165.

Loveridge, A. (1944) New geckos of the genera *Afroedura*, new genus, and *Pachydactylus* from Angola. *American Museum Novitates,* **1254**, 1–4.

Mertens, R. (1938) Amphibien und Reptilien aus Angola gesammelt von W. Schack. *Senckenbergiana*, **20**, 425–443.

Monard, A. (1937a) Contribuition à la batrachologie d'Angola. *Bulletin de la Société Neuchâteloise des Sciences Naturelles,* **62**, 1–59.

Monard, A. (1937b) Contribution à l'herpétologie d'Angola. *Arquivos do Museu Bocage,* **8**, 19–154.

National Biodiversity Strategy and Action Plan (NBSAP) (2006). Ministry of Urban Affairs and Environment, Republic of Angola, Luanda.

Parker, H.W. (1936) Dr. Karl Jordan's expedition to South West Africa and Angola: herpetological collection. *Novitates Zoologicae,* **40**, 115–146.

Perret, J.-L. (1976) Révision des amphibiens africains et principalement des types, conservés au Musée Bocage de Lisbonne. *Arquivos do Museu Bocage, Segunda Série*, **6**, 15–34.

Poynton, J.C. & Haacke, W.D. (1993) On a collection of amphibians from Angola, including a new species of *Bufo* Laurenti. *Annals of the Transvaal Museum*, **36**, 9–16.

Poynton, J.C., Loader, S.P., Conradie, W., Rödel, M.O. & Liedtke, H.C. (2016) Designation and description of a neotype of *Sclerophrys maculata* (Hallowell, 1854), and reinstatement of *S. pusilla* (Mertens, 1937) (Amphibia: Anura: Bufonidae). *Zootaxa*, **4098**, 73–94.

Ruas, C. (1996) Contribuição para o conhecimento da fauna de batráquios de Angola. *Garcia de Orta. Serie de Zoologia, Lisboa,* **21**, 19–41.

Schmidt, K.P. (1933) The reptiles of the Pulitzer Angola expedition. *Annals of the Carnegie Museum*, **22**, 1–15.

Schmidt, K.P. (1936) The amphibians of the Pulitzer-Angola Expedition. *Annals of the Carnegie Museum*, **25**, 127–133.

Smith, W.H. & Rissler, L.J. (2010) Quantifying disturbance in terrestrial communities: abundance–biomass comparisons of herpetofauna closely track forest succession. *Restoration Ecology*, **18**, 195–204.

Stanley, E., Ceríaco, L.M.P., Bandeira, S., Valerio, H., Bates, M.F. & Branch, W.R. (2016) A new species of *Cordylus* (Squamata: Cordylidae) from the ProNamib of south-western Angola. *Zootaxa*, **4061**, 201–226.

Uetz, P., Freed, P. & Hošek, J. (eds.), *The Reptile Database.* Electronic database accessible at http://www.reptile-database.org (accessed 28 June 2017)

References [CrossRef]

BirdLife International (2017) Important Bird Areas factsheet: Tundavala. Downloaded from http://www.birdlife.org on 28 June 2017.

Bocage, J.V.B. (1870) Description d'un "Saurien" nouveau de l'Afrique occidentale. *Jornal de Sciencias Mathematicas, Physicas e Naturaes*, **3**, 66–68.

Bocage, J.V.B. (1872) Diagnoses de quelques espéces nouvelles de Reptiles d'Afrique occidentale. *Jornal de Sciencias Mathematicas, Physicas e Naturaes*, **4**, 72–82.

Bocage, J.V.B. (1895) *Herpétologie d'Angola et du Congo*. Ministério da Marinha e das Colónias, Lisbon.

Bogert, C.M. (1940) Herpetological results of the Vernay Angola Expedition with notes on African reptiles in other collections. Part 1, Snakes, including an arrangement of African Colubridae. *Bulletin of the American Museum of Natural History*, **77**, 1–107.

Boulenger, G.A. (1905) A list of the batrachians and reptiles collected by Dr. W.J. Ansorge in Angola, with descriptions of new species. *Annals and Magazine of Natural History*, ser. 7, **16**, 8–115.

Branch, W.R. (1998) *Field guide to snakes and other reptiles of southern Africa*. Struik. Cape Town.

Broadley, D.G. (1977) A revision of the African snake genus *Psammophylax* Fitz Ingersoll (Colubridae). *Arnoldia (Rhodesia)*, **8**, 1–44.

Channing, A. (2001) *Amphibians of central and southern Africa*. Comstock Pub. Associates. Cornell University Press. New York.

Channing, A., Rödel, M.O. & Channing, J. (2012) *Tadpoles of Africa: The biology and identification of all known tadpoles in sub-Saharan Africa*. Edition Chimaira, Frankfurt.

Channing, A., Hillers, A., Lötters, S., Rödel, M.O., Schick, S., Conradie, W., Rödder, D., Mercurio, V., Wagner, P., Dehling, J.M., Du Preez, L.H., Kielgast, J. & Burger, M. (2013) Taxonomy of the super-cryptic *Hyperolius nasutus* group of long reed frogs of Africa (Anura: Hyperoliidae), with descriptions of six new species. *Zootaxa*, ***3620***, 301–350.

Clark, V.R., Barker, N.P. & Mucina, L. (2011) The Great Escarpment of southern Africa: a new frontier for biodiversity exploration. *Biodiversity and Conservation*, **20**, 2543–2561. CrossRef

Conradie, W., Bills, R. & Branch, W.R. (2016) The herpetofauna of the Cubango, Cuito, and lower Cuando river catchments of south-eastern Angola. *Amphibian & Reptile Conservation*, **10**, 6–36.

Conradie, W., Branch, W.R., Measey, G.J. & Tolley, K.A. (2012) A new species of *Hyperolius* Rapp, 1842 (Anura: Hyperoliidae) from the Serra da Chela mountains, south-western Angola. *Zootaxa*, **3269**, 1–17.

Crawford-Cabral, J. & Mesquitela, L.M. (1989) Índice toponímico de colheitas zoológicas em Angola (Mammalia, Aves, Reptilia e Amphibia). *Estudos, ensaios e documentos.* Instituto de Investigação Científica Tropical,Lisboa, 206 pp.

Ferreira, J.B. (1904) Reptis e amphibios de Angola da região ao norte do Quanza (Collecção Newton – 1903). *Jornal de Sciencias Mathematicas, Physicas e Naturaes, Segunda Série*, **7**, 111–117.

Ferreira, J.B. (1906) Algumas espécies novas ou pouco conhecidas de amphibios e reptis de Angola (Collecção Newton – 1903–1904). *Jornal de Sciencias Mathematicas, Physicas e Naturaes, Segunda Série*, **7**, 159–171.

FitzSimons, V. (1959) Some new reptiles from southern Africa and southern Angola. *Annals of the Transvaal Museum*, **23**, 405–409.

Frost, Darrel R. (2017) Amphibian species of the world: an online reference, version 6.0 (28 June 2017). American Museum of Natural History, New York, USA. Electronic database accessible at http://research.amnh.org/herpetology/amphibia/index.html

Haacke, W. (1997) Systematics and biogeography of the southern African scincine genus *Typhlacontias* (Reptilia: Scincidae). *Bonner zoologische Beitrage*, **47**, 139–164.

Haacke, W.D. (2008) A new leaf-toed gecko (Reptilia: Gekkonidae) from south-western Angola. *African Journal of Herpetology*, **57**, 85–92. CrossRef

Hall, B.P. (1960) The faunistic importance of the scarp of Angola. *Ibis*, **102**, 420–442. CrossRef

Hellmich, W. (1957) Herpetologische Ergebnisse einer Forschungsreise in Angola. *Veröffentlichungen der Zoologischen Staatssammlung München*, **5**, 1–92.

Hoffman, L.A.C. (1989) An annotated list of amphibian and reptile observations from the Etosha National Park. *Madoqua*, **16**, 87–92.

Huntley, B.J. (1974) Outlines of wildlife conservation in Angola. *South African Journal of Wildlife*, **4**, 157–166.

Huntley, B.J. & Matos, E.M. (1994) Botanical diversity and its conservation in Angola. *Strelitzia*, **1**, 53–74.

Laurent, R.F. (1952) Reptiles et batraciens nouveaux du massif du mont Kabobo et du plateau des Marungu. *Revue de Zoologie et de Botanique Africaines*, **46**, 18–34.

Laurent, R.F. (1954) Reptiles et batraciens de la région de Dundo (Angola) (Deuxième note). *Publicações Culturais da Companhia de Diamantes de Angola*, **23**, 35–84.

Laurent, R.F. (1964) Reptiles et amphibiens de l'Angola (Troisème contribution). *Publicações Culturais. Companhia de Diamantes de Angola, Lisboa*, **67**, 1–165.

Loveridge, A. (1944) New geckos of the genera *Afroedura*, new genus, and *Pachydactylus* from Angola. *American Museum Novitates*, **1254**, 1–4.

Mertens, R. (1938) Amphibien und Reptilien aus Angola gesammelt von W. Schack. *Senckenbergiana*, **20**, 425–443.

Monard, A. (1937a) Contribution à la batrachologie d'Angola. *Bulletin de la Société Neuchâteloise des Sciences Naturelles*, **62**, 1–59.

Monard, A. (1937b) Contribution à l'herpétologie d'Angola. *Arquivos do Museu Bocage*, **8**, 19–154.

National Biodiversity Strategy and Action Plan (NBSAP) (2006). Ministry of Urban Affairs and Environment, Republic of Angola, Luanda.

Parker, H.W. (1936) Dr. Karl Jordan's expedition to South West Africa and Angola: herpetological collection. *Novitates Zoologicae*, **40**, 115–146.

Perret, J.-L. (1976) Révision des amphibiens africains et principalement des types, conservés au Musée Bocage de Lisbonne. *Arquivos do Museu Bocage, Segunda Série*, **6**, 15–34.

Poynton, J.C. & Haacke, W.D. (1993) On a collection of amphibians from Angola, including a new species of *Bufo* Laurenti. *Annals of the Transvaal Museum*, **36**, 9–16.

Poynton, J.C., Loader, S.P., Conradie, W., Rödel, M.O. & Liedtke, H.C. (2016) Designation and description of a neotype of *Sclerophrys maculata* (Hallowell, 1854), and reinstatement of *S. pusilla* (Mertens, 1937) (Amphibia: Anura: Bufonidae). *Zootaxa*, **4098**, 73–94. CrossRef

Ruas, C. (1996) Contribuição para o conhecimento da fauna de batráquios de Angola. *Garcia de Orta. Serie de Zoologia, Lisboa*, **21**, 19–41.

Schmidt, K.P. (1933) The reptiles of the Pulitzer Angola expedition. *Annals of the Carnegie Museum*, **22**, 1–15.

Schmidt, K.P. (1936) The amphibians of the Pulitzer-Angola Expedition. *Annals of the Carnegie Museum*, **25**, 127–133.

Smith, W.H. & Rissler, L.J. (2010) Quantifying disturbance in terrestrial communities: abundance–biomass comparisons of herpetofauna closely track forest succession. *Restoration Ecology*, **18**, 195–204. CrossRef

Stanley, E., Ceríaco, L.M.P., Bandeira, S., Valerio, H., Bates, M.F. & Branch, W.R. (2016) A new species of *Cordylus* (Squamata: Cordylidae) from the ProNamib of south-western Angola. *Zootaxa*, **4061**, 201–226. CrossRef

Uetz, P., Freed, P. & Hošek, J. (eds.), *The Reptile Database*. Electronic database accessible at http://www.reptile-database.org (accessed 28 June 2017)

Biodiversity

Annotated checklist of cockroaches and termites of Zambia (Arthropoda: Insecta; Blattodea)

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Abstract: An annotated checklist of cockroaches and termites (order Blattodea) was compiled for Zambia based on intensive reviews of literature on insects of the country. Furthermore, field surveys were performed to confirm some of these records in the last five years (March 2013 - October 2017). The checklist contains 27 genera of cockroaches in Zambia, containing 43 species and three subspecies. The epifamily Termitoidae comprises 38 genera, 87 species, and one subspecies of termites in the country. The occurrence of seven species of cockroaches and two species of termites in Zambia was confirmed during the biodiversity field surveys. Statuses of some termite species, particularly those of the genus Macrotermes Holmgren, 1909, are controversial in Zambia, as they are viewed as crop pests on one hand and as human food on the other. All species of the Blattodea in Zambia are registerd as 'not evaluated' in the IUCN Red List.

Resumo: Foi compilada uma lista anotada de baratas e térmitas (Ordem Blattodea) para a Zâmbia, com base nas revisões intensivas da literatura sobre insectos do país. Além disso, foram realizados estudos de campo nos últimos cinco anos (Março 2013 – Outubro 2017) para confirmar alguns desses registos. A lista contém 27 géneros de baratas da Zâmbia, contendo 43 espécies e três subespécies. A epifamilia Termitoidae inclui 38 géneros, 87 espécies e uma subespécie de térmitas do país. A ocorrência de sete espécies de baratas e duas espécies de térmitas na Zâmbia foi confirmada durante os levantamentos de biodiversidade. Os estados de algumas espécies de térmitas, particularmente aquelas do género Macrotermes Holmgren, 1909, são controversos na Zâmbia, pois são vistos, por um lado, como pragas de culturas e, por outro, como alimento humano. Todas as espécies de Blattodea na Zâmbia estão registadas como "não avaliadas" pela Lista Vermelha do UICN.

Introduction

As a signatory to the International Convention on Biological Diversity (CBD), which was ratified on 8 May 1998, Zambia is expected to: conserve its genetic, species and ecosystem diversity; use its biodiversity components sustainably; and share the benefits derived from the use of its genetic resources equitably among its citizenry. The development of biodiversity conservation programmes in the country is, however, rendered difficult by the scarcity of information available on the country's biodiversity, which is needed to develop the programmes. It goes without saying that in order for a country to conserve its biodiversity and other natural resources effectively, it needs to know what is there in the country to conserve, in the first place, and why, in the second place. There is therefore a need for more, reliable and updated information on Zambia's biodiversity, generated through intensive literature reviews and biodiversity field surveys in the country, to develop reliable biodiversity conservation programmes.

The formulation of the country's first National Biodiversity Strategy and Action Plan (NBSAP1) in Zambia which operationalized the CBD, was based on the very little information available at the time and that which was gathered through a one-month-long country study on the country's biodiversity undertaken in 1998 (Chidumayo & Aongola, 1998; Mbata, 1998; Ministry of Environment and Natural Resources [MENR], 1998). The country study was sanctioned by the MENR and sponsored by the International Union for Conservation of Nature (IUCN). In 2015 the Ministry of Lands, Natural Resources and Environmental Protection (MLNREP) carried out a revision of NBSAP1 aimed at harmonizing it with (a) the country's new development trajectory, (b) challenges related to climate change, and (c) the Global Strategic Plan on Biodiversity (2011 - 2020) as well as the Aichi Biodiversity Targets under the CBD of 2010, both of which the country had adopted. This drafting of the NBSAP2 did not help matters, as no additional data on the country's biodiversity was collected from the field.

Regarding the present status of collected Blattodea species in Zambia, the collection is stored in the Livingstone National Museum, the largest and oldest museum in the country. It was established in 1934 during the colonial days as the David Livingstone Memorial Museum and was also formerly called Rhodes-Livingstone Museum. Its year 1999 - insect collection register, examined by the author in 2014, has on record

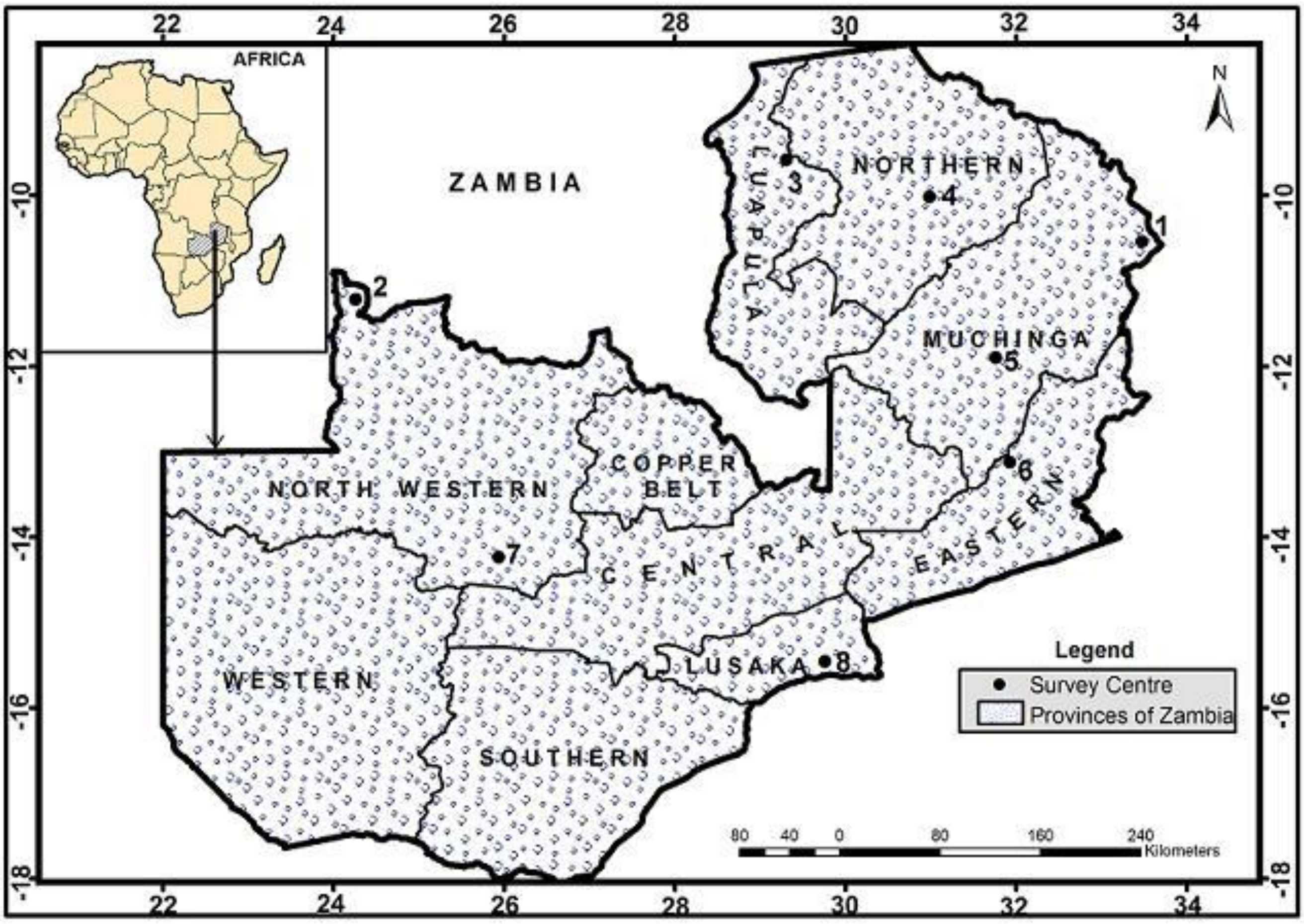

Figure 1: Map of Zambia showing provinces and field biodiversity survey centres. 1: Chowo forest, Nyika National Park. 2: Source of the Zambezi River. 3: Lumangwe Falls area. 4: Chishimba Falls area. 5: North Luangwa National Park. 6: South Luangwa National Park. 7: Treetops school camp, Kafue National Park. 8: Chakwenga, Lower Zambezi National Park.

25 genera and 52 species of termites and 470 termite specimens that were identified only to the genus level. The termite collection is a relatively recent one. The oldest specimen, identified to genus level only, is *Macrotermes* sp., collected from Lusaka by M. G. Bingham. The most recent termite specimen, also identified only to genus level is *Trinervitermes* sp., collected in 1982 by P. Nkunika from Lochinvar National Park in Monze, Southern Province. Suprisingly enough, the Livingstone National Museum had no specimens of cockroaches of Zambia at the time of the author's visit in 2014.

This gap in knowledge on Zambia's biodiversity has now started to be filled up through a five-year project on Zambia's biodiversity known as, the Baseline Inventory of Zambia's Biodiversity. The author is working on Zambia's invertebrates for the project, while four other researchers are concerned with vertebrates and lower and higher plants. This paper reports on an annotated checklist developed for cockroaches and termites of Zambia.

Study area

For the literature study, the entire country of Zambia was considered. Field surveys were carried out in six selected study areas throughout the country. Zambia lies on the anterior African high plateau, between 1000 m and 1600 m above sea level, consisting mainly of a series of gently undulating to flat plateaux occasionally broken by isolated hills or low ranges of resistant rocks (Davies, 1971). The field surveys were carried out in representative areas of the country selected based on criteria including accessibility by road and pristineness of the area. Areas with comparatively little human disturbance were preferred. We carried out surveys in Nyika National Park on the Nyika Plateau in Muchinga Province, in the northeast of the country; the source of the Zambezi River in the North-Western Province; Luapula and Northern Provinces; North and South Luangwa National Parks; Lower Zambezi National Park; and Kafue National Park (KNP) (Fig. 1). The latter is the largest national park in the country and the fifth largest in Africa.

Zambia has three distinct seasons – namely, a rainy season (November–April), a cool dry season (May/June–August), and a hot dry season (September–October/November). The relatively high altitude gives the country pleasant subtropical weather during the cool dry season but the average monthly temperatures remain above 20 °C over most of the country for eight or more months of the year.

There are 14 ecosystems in the country, classed into the Forest, Thicket, Woodland, and Grassland vegetation types (Worldatlas.com., 2018), and the country is divided into ten administrative provinces (Fig. 1).

Materials and methods

The study involved intensive literature surveys on what is known about the diversity of cockroaches and termites (Order Blattodea) in Zambia, as information on the country's biodiversity in general, and the invertebrates, in particular, is very scanty in the literature. Few researchers have worked on the biodiversity of Zambia in the past. For example, Pinhey (1961, 1975), reported on dragonflies and insects of Zambia, while Pinhey & Loe (1973, 1977) produced guides to the insects and butterflies of Zambia. No specific study has been done in the past on cockroaches of the country, but regarding termites, Nkunika (1982, 1986) pioneered the preparation of termite checklists in the country. He published a preliminary checklist of termites of the Southern Province of the country and one for Lochinvar National Park in the same province. The present study involved reviews of the above-mentioned literature plus many more that the author came across scattered over the Internet that examine cockroaches and termites of Zambia and the southern Africa region. Further information on invertebrates of Zambia in the form of preserved specimens in the nation's major animal species repository was accessed by visiting the country's Livingstone National Museum.

Some of the cockroach and termite species recorded to occur in Zambia in the literature were confirmed in this study through identifications of specimens collected by the author and his research team through field biodiversity surveys undertaken in selected parts of the country (Fig. 1) during the study: Nyika National Park on the Nyika Plateau plateau in Muchinga Province, in the northeast of the country; the source of the Zambezi River in the Northwestern Province; Luapula and Northern Provinces; North and South Luangwa National Parks; Lower Zambezi National Park; and Kafue National Park (KNP). The latter is the largest national park in the country and the fifth largest in Africa. The selection of the parts of the country in which to conduct biodiversity surveys was based on the area's accessibility by road and their pristineness. Areas with comperatively little human disturbace were preferred.

The number of sampling sites selected in each survey centre depended on the vegetation types occurring in the survey centre. Each vegetation type had one sampling site selected in it. An average of four sampling sites were established at each survey centre. Two 100 x 0.25 m transects spaced 50 m apart were set in each chosen sampling site, and cockroaches and termites ecountered along each transect on vegetation and in the litter were collected using hands, forceps, and aerial insect nets. No termite mounds were dug up along the transects to collect termites. Only termites found on the surface in litter and on vegetation were collected for identification. Collected insects were preserved in 70% ethanol in well-labelled bottles and taken for identification to the University of Zambia, Department of Biological Sciences, in Lusaka.

Taxonomic identification keys (e.g., Krishna et al., 2013; Marshall, 1989; Pratt, 2017; Ruelle, 1989; Sands, 1998; Victor, 1941), photographs and comparisons of the specimens with already identified and confirmed preserved specimens in the Livingstone National Museum and in the teaching insect collections of the Department of Biological Sciences at the University of Zambia in Lusaka were used to identify the collected termite and cockroach species.

Results

The checklist

The checklist of cockroaches and termites known to occur in Zambia is presented in Tables 1 to 5 below.

General remarks

Each species or subspecies entry in the checklist is divided into the following columns:

Synonym(s):

The alternative valid name(s) of the species or subspecies is presented in this column. If a name of a species or subspecies has many synonyms, only five were selected and the number of remaining ones given.

Distribution:

The column presents the geographical distribution of the species or subspecies in the world.

Location in Zambia:

All locations within Zambia where the species or subspecies was collected are listed in this column.

Note:

Species or subspecies that have been confirmed to occur in Zambia through the biodiversity field surveys conducted by the author (2013–2017) are marked with an asterisk in the checklist (*), while the localities in Zambia where the species or subspecies were collected in the field surveys are marked with a double asterisk (**).

Table 1: Checklist of Blattodea of Zambia: Family Blattidae.

Family	Scientific name	Synonym(s)	Distribution	Location in Zambia
Superfamily BLATTOIDEA: Epifamily Blattoidae.				
Blattidae	***Blatta orientalis* Linnaeus, 1758. ***	*Blatta badia* (Saussure, 1863); *Blatta castanea* (Blanchard, 1851); *Blatta culinaris* (De Geer, 1773); *Blatta europaea* (Bartsch, 1846); *Blatta europea* (Bartsch, 1846) + 20.	Cosmopolitan in temperate regions [southern Russian origin]. Has been introduced to many other parts of the world. The Oriental Cockroach is common world-wide. There is no country that is free of the presence of this insect (Plant Pests and Diseases Act. No. 13. 1994; IUCN Red List of Threatened Species. Version 2016-3; Mbata, 1998; Ministry of Environment and Natural Resources (MENR), 1998).	Lusaka** in Lusaka Province; Livingstone in Southern Province.
	***Cartoblatta barbara* (Shelford, 1911).**	*Blatta barbara* (Shelford, 1911).	Burundi, Democratic Republic of Congo, Zambia (Beccaloni, 2014).	Chingola, Copperbelt Province.
	***Cartoblatta pulchra* Shelford, 1910.**	*Periplaneta transvaalensis* Rehn, 1922.	Kenya, Malawi, Mozambique, South Africa, Tanzania, Zambia, Zimbabwe (Beccaloni, 2014; Catalogue of life, 2016).	Lusaka and Kafue, Lusaka Province.
	***Deropeltis comosa* Rehn, 1922.**	None.	Kenya, Mozambique, South Africa, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species, 2016).	Chiawa, Middle Zambezi valley, Lusaka Province.
	***Deropeltis melanophila* (Walker, 1869).**	*Deropeltis speiseri* Brancsik, 1896; *Ischnoptera melanophila* Walker, F., 1869.	Cameroon, Ethiopia, Kenya, Mozambique, South Africa, Tanzania, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species, 2016).	Gorges east of Victoria Falls, Livingstone, in Southern Province.
	***Deropeltis paulinoi* Bolivar, 1881.**	None.	Angola, Democratic Republic of Congo, Mozambique, Namibia, South Africa, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species, 2016).	Mkushi, in Central Province.
	***Deropeltis wahlbergi* (Stål, 1856).**	*Deropeltis nubila* Rehn, 1922; *Periplaneta wahlbergi* (Stal, 1856).	Mozambique, South Africa, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014).	Chingola, in Copperbelt Province.
	***Neostylopyga rhombifolia* (Stoll, 1813).**	*Blatta rhombifolia* (Stoll, 1813); *Blatta signata* Eschscholtz, 1822; *Neostylopyga histrio* (Saussure, 1864); *Neostylopyga signata* (Eschscholtz, 1822); *Periplaneta decorata* Brunner von Wattenwyl, 1865 + 2.	Circumtropical [Asian origin]; China, El Salvador, Germany, India, Indonesia, Madagascar, Malaysia, Mexico, Netherlands, Sweden, Taiwan, Tanzania, United Kingdom, USA (Texas), Zambia (Catalogue of life, 2016; Beccaloni, 2014).	Mbala, Northern Province.
	***Periplaneta americana* (Linnaeus, 1758). ***	*Blatta americana* Linnaeus, 1758; *Blatta aurelianensis* Fourcroy, 1785; *Blatta domicola* Risso, 1826; *Blatta ferrugineofusca* Gronovius, 1764; *Blatta heros* Eschscholtz, 1822 + 9.	Cosmopolitan [African origin]; Africa – Algeria, Botswana, Cameroon, Ghana, Kenya, Madagascar, Malawi, Morocco, Mozambique, Namibia, Nigeria, Senegal, South Africa, Sudan, Tanzania, Tunisia, Uganda, Zambia, Zimbabwe etc., (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species, 2016-3).	Lusaka** and Kafue**, in Lusaka Province; Monze**, Pemba, Choma** and Livingstone**, in Southern Province; Chingola, Chililabombwe and Ndola**, in Copperbelt Province; Kasama and Mbala, in Northern Province; Solwezi and Ikelenge** in Northwestern Province; Mongu and Kalabo in Western Province. Mpika in Muchinga Province; Chipata in Eastern Province (Mbata, 1998; Ministry of Environment and Natural Resources 1998).
	***Pseudoderopeltis anthracina* (Brancsik, 1896).**	*Pseudoderopeltis brancsiki* (Shelford, 1910); *Stylopyga anthracina* (Brancsik, 1896); *Stylopyga brancsiki* (Shelford, 1910).	Malawi, Mozambique, Tanzania, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Lusaka and Kafue, in Lusaka Province.
	***Pseudoderopeltis caffra caffra* (Stål, 1856).**	*Periplaneta caffra* (Stål, 1856)	Botswana, Mozambique, South Africa, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014).	Gorges east of Victoria Falls, Livingstone, in Southern Province.
	***Pseudoderopeltis caffra vicina* Princis, 1955.**	*Pseudoderopeltis vicina* Princis, 1955	Burkina Faso, Burundi, Rwanda, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014).	Solwezi, in Northwestern Province (Catalogue of life, 2016; Cockroach species file, 2016).
	***Pseudoderopeltis diluta* (Stål, 1856).**	*Periplaneta africana* Karny, 1908; *Periplaneta diluta* Stål, 1856.	Botswana, Namibia, South Africa, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; Pinhey, 1975).	Victoria Falls region at gorges east of the Victoria Falls, Livingstone, Southern Province.
	***Pseudoderopeltis inermis* Princis, 1963.**	None.	South Africa, Zambia (Catalogue of life, 2016; Beccaloni, 2014).	Chilanga, Lusaka Province.
	***Pseudoderopeltis transvaalensis* Rehn, 1922.**	None.	Mozambique, Namibia, South Africa, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014).	Kapiri Mposhi, in Central Province.

Biodiversity

Table 2: Checklist of Blattodea of Zambia: Family Termitidae.

Family	Scientific name	Synonym(s)	Distribution	Location in Zambia
Superfamily BLATTOIDEA: Epifamily Termitoidae				
Termitidae	***Acholotermes epius* Sands, 1972**	None	Zambia, Zimbabwe (Krishna et al., 2016; Nkunika, 1982; Sands, 1998).	Lusaka (Type locality), in Lusaka Province.
	***Acholotermes imbellis* Sands, 1972.**	None.	Democratic Republic of Congo, Zambia (Livingstone National Museum Collection, Zambia).	Lusaka, in Lusaka Province.
	***Adaiphrotermes scapheutes* Sands, 1972.**	None.	Malawi; Zambia (Krishna et al., 2016; Sands, 1998).	Kitwe (Type locality), in Copperbelt Province.
	***Aderitotermes fossor* Sands, 1972.**	None.	Cameroon; Kenya; Malawi; Tanzania; Uganda; Zambia (Krishna et al., 2016; Sands, 1998).	Kabwe, in Central Province.
	***Aganotermes oryctes* Sands, 1972.**	None.	South Africa, Zambia, Zimbabwe (Krishna et al, 2016; Nkunika, 1982, 1986; Sands, 1998).	Livingstone, in Southern Province.
	***Allodontermes rhodesiensis* (Sjöstedt, 1914).**	*Termes (Allodontermes) rhodesiensis* Sjöstedt, 1914; *Allodontermes schultzei orientalis* Fuller, 1922; *Termes* (*Protermes*) *esuriens* Sjöstedt, 1924; *Termes liber* Van Boven, 1969.	Mozambique, Namibia, South Africa, Swaziland, Zambia, Zimbabwe (Nkunika, 1982: Ruelle, 1979).	Southern Province.
	***Allodontermes schultzei* (Silvestri, 1908).**	*Termes schultzei* Silvestri, 1908.	Botswana, Namibia, South Africa, Swaziland, Zambia, Zimbabwe (Nkunika, 1982, 1986; Ruelle, 1979).	Southern Province.
	***Allodontermes tenax* (Silvestri, 1912).**	*Termes* (*Allodontermes*) *tenax* Silvestri, 1912; *Termes tenax* Silvestri, 1912	Democratic Republic of Congo, Kenya, Malawi, Mozambique, Tanzania, Zambia, Zimbabwe (Hocking, 1965; Nkunika, 1982, 1986; Ruelle, 1979).	Livingstone, in Southern Province.
	***Amitermes importunus* Sands, 1959.**	None.	Malawi, Zambia, Zimbabwe (Bouillon and Mathot, 1965; Nkunika, 1982; Sands 1959, 1992, 1998).	Southern Province.
	***Amitermes messinae* (Fuller, 1922).**	*Amitermes harleyi* Harris, 1957; *Hamitermes messinae* Fuller, 1922.	Egypt, Iran, Kenya, Malawi, Saudi Arabia, South Africa, Sudan, Tanzania, Yemen, Zambia (Krishna et al., 2016; Nkunika, 1982).	Southern Province.
	***Amitermes truncatidens* Sands, 1959.**	None	Democratic Republic of Congo, Malawi, Tanzania, Zambia, Zimbabwe (Bouillon and Mathot, 1965; Nkunika 1982, 1986; Sands 1992, 1998).	Southern Province.
	***Amitermes unidentatus* (Wasmann, 1897).**	*Amitermes macrocephalus* Ghidini, 1941; *Eutermes meruensis* Sjöstedt, 1911; *Hamitermes elongatus* Silvestri, 1914; *Hamitermes limpopoensis* Fuller, 1922; *Termes unidentatus* Wasmann, 1897.	Democratic Republic of Congo, Ethiopia, Kenya, Malawi, Rwanda, South Africa, Sudan, Tanzania, Uganda, Zambia (Krishna et al., 2016).	Lusaka, in Lusaka Province.
	***Ancistrotermes latinotus* (Holmgren, 1912).**	*Ancistrotermes lebomboensis* Fuller, 1922; *Microtermes latinotus* Holmgren, 1912; *Termes crucifer* Sjöstedt 1900.	Central African Republic, Congo-Brazaville, Democratic Republic of Congo, Ethiopia, Kenya, Malawi, Mozambique, South Africa, Swaziland, Tanzania, Uganda, Zambia, Zimbabwe (Bouillon and Mathot, 1966; Coaton and Sheasby, 1975; Harris, 1966; Nkunika 1982, Nkunika, 1986; Wood and Tomas, 1989).	Southern Province.
	***Anenteotermes disluctans* Sands, 1972.**	*Anoplotermes luescheri* Mathur and Thapa, 1962.	Congo-Brazzaville, Democratic Republic of Congo, Uganda, Zambia (Nkunika 1982, 1986; Sands, 1998.).	Southern Province.
	***Angulitermes truncatus* Sjöstedt, 1926.**	None.	Ghana, Kenya, Nigeria, Senegal, Tanzania, Uganda, Zambia, Palaearctic Region [Saudi Arabia] (Krishna et al., 2016; Nkunika, 1982).	Lochinvar National Park, Monze, Southern Province.
	***Astalotermes brevior* (Holmgren, 1913).**	*Anoplotermes sanctus* Silvestri, 1914; *Mirotermes* (*Procubitermes*) *mbazwanicus* Fuller, 1925; *Mirotermes* (? *Procubitermes*) *mfolozii warreni* Fuller, 1925; *Mirotermes* (*Cubitermes*) *natalensis brevior* Holmgren, 1913.	Angola, Namibia, South Africa, Swaziland, Zambia, Zimbabwe (Nkunika, 1982; Sands, 1972, 1998).	Southern Province.
	***Astalotermes impedians* Sands, 1972.**	None.	Zambia (Krishna et al., 2016; Sands, 1972).	Ndola (Type locality), in Copperbelt Province.
	***Astalotermes murcus* Sands, 1972.**	None.	Congo-Brazaville, Zambia (Krishna et al., 2016; Sands, 1998).	Ndola (Type locality), in Copperbelt Province.
	***Astratotermes aneristus* Sands, 1972.**	None.	Zambia (Krishna et al., 2016; Sands, 1998).	Kitwe (Type locality), in Copperbelt Province.
	***Crenetermes albotarsalis* (Sjöstedt, 1897).**	*Eutermes albotarsalis* Sjöstedt, 1897.	Cameroon, Congo-Brazzaville, Congo-Zaire [Now, Democratic Republic of Congo], Gabon, Nigeria, Rwanda, Tanzania, Zambia (Bouillon and Mathot, 1965; Harris, 1951).	Kabwe, in Central Province.
	***Cubitermes inclitus* Silvestri, 1912.**	*Cubitermes bilobatus inclitus* Silvestri, 1912; *Eutermes* (*Cubitermes*) *domifaber* Sjöstedt, 1913.	Congo-Brazzaville, Congo-Zaire [Now, Democratic Republic of Congo], Kenya, Malawi, Rwanda, Tanzania, Uganda, Zambia (Bouillon and Mathot, 1966; Snyder, 1949; Williams, 1966).	Type locality: Zambia [formerly, Northern Rhodesia], Banguelo (Lake Bangweulu area), Samfya, in Luapula Province. Also collected on Ndola-Kitwe road, in the Copperbelt Province; and in Abercorn [Now Mbala], in Northern Province.
	***Cubitermes minitabundus* (Sjöstedt, 1913).**	*Eutermes* (*Cubitermes*) *minitabundus* Sjöstedt, 1913; *Isognathotermes minitabundus* Sjöstedt, 1926.	Congo-Zaire [Now, Democratic Republic of Congo], Malawi, Zambia (Bouillon and Mathot, 1966; Hocking, 1965; Sands, 1998; Williams, 1966).	Chingola, Nchanga, Ndola-Kitwe road and Kitwe-Dola Hill road, in Copperbelt Province; 8.045 km north of Chembe ferry, Luapula R., in Luapula Province; and Abercorn [Now Mbala], in Northern Province.
	***Cubitermes montanus* Williams, 1966.**	None.	Malawi, Tanzania, Zambia (Bouillon and Mathot, 1966; Nkunika, 1982).	Southern Province.
	***Cubitermes muneris* (Sjöstedt, 1913).**	*Cubitermes bisulcatus* (Sjöstedt, 1914); *Cubitermes muneris* Sjöstedt, 1926; *Eutermes* (*Cubitermes*) bisulcatus Sjöstedt, 1914; *Eutermes* (*Cubitermes*) *muneris* Sjöstedt, 1913.	Congo-Zaire [Now Democratic Republic of Congo], Kenya, Malawi, Tanzania, Zambia (Bouillon and Mathot, 1966; Nkunika, 1982; Sands, 1998; Williams, 1966).	Southern Province; Kitwe-Dola Hill road., Ndola=Kitwe road, in Copperbelt Province; Abercorn [Now Mbala], in the Northern Province; and the Zambian environs of Tunduma in Muchinga Province.
	***Cubitermes oblectatus* Harris, 1958.**	None.	Congo-Zaire [Now, Democratic Republic of Congo], Malawi, Tanzania, Zambia (Bouillon and Mathot, 1966; Williams, 1966).	Abercorn [Now Mbala], in Northern Province; Nakonde, in Muchinga Province.
	***Cubitermes orthognathus* (Emerson, 1928).**	*Mirotermes* (*Cubitermes*) *orthgnathus* Emerson, 1928.	Congo-Zaire [Now, Democratic Republic of Congo], Kenya, Malawi, Tanzania, Uganda, Zambia (Bouillon and Mathot, 1966; Nkunika, 1982; Sands, 1998; Williams, 1966).	Southern Province.
	***Cubitermes pallidiceps* (Sjöstedt, 1913)**	*Eutermes* (*Cubitermes*) *pallidiceps* Sjöstedt, 1913.	Congo-Zaire [Now, Democratic Republic of Congo], Malawi, Tanzania, Zambia, Zimbabwe (Bouillon and Mathot, 1966; Williams, 1966).	Solwezi, in Northwestern Province.
	***Cubitermes sanctaeluciae* (Fuller, 1925).**	*Mirotermes* (*Cubitermes*) *sanctaeluciae* Fuller, 1925.	South Africa, Zambia (Sands, 1998).	Lusaka and Kafue, in Lusaka Province.

Family	Scientific name	Synonym(s)	Distribution	Location in Zambia
	***Cubitermes sankurensis* Wasmann, 1911.**	*Cubitermes sankurensis elongata* Sjöstedt, 1926 [junior homonym of *Cubitermes fungifaber elongata* Sjöstedt, 1924; replacement name needed if taxon is removed from synonymy]; *Eutermes* (*Cubitermes*) *cubicephalus* Sjöstedt, 1913; *Eutermes sibitiensis* Sjöstedt, 1925.	Angola, Congo-Brazzaville, Congo-Zaire [Now, Democratic Republic of Congo], Kenya, Malawi, Tanzania, Zambia, Zimbabwe (Bouillon and Mathot, 1966; Hocking, 1965; Williams, 1966).	Luapula River at Chembe Ferry, Lake Bangweulu at Samfya, in Luapula Province; Ndola, Dola Hill, in the Copperbelt Province; Abercorn [Now Mbala], in Northern Province.
	***Cubitermes tenuiceps* (Sjöstedt, 1913).**	*Eutermes* (*Cubitermes*) *tenuiceps* Sjöstedt, 1913.	Congo-Zaire [Now Democratic Republic of Congo], Malawi, Tanzania, Zambia (Bouillon and Mathot, 1966; Nkunika 1982, 1986; Williams, 1966).	Kafue R., Mazabuka rd., in Southern Province; 30 m. W. of Mumbwa, in Central Province.
	***Cubitermes transvaalensis* (Fuller, 1925).**	*Mirotermes* (*Cubitermes*) *transvaalensis* Fuller, 1925.	South Africa; Zambia (Nkunika 1982, 1986).	Southern Province.
	***Cubitermes ugandensis* Fuller, 1923.**	*Cubitermes antennalis* Sjöstedt, 1924.	Congo-Zaire [Now, Democratic Republic of Congo], Kenya, Malawi, Rwanda, Tanzania, Uganda, Zambia (Bouillon and Mathot, 1966; Williams, 1966).	Bangweulu environs including Samfya in Luapula Province; near Tunduma in Muchinga Province.
	***Enetotermes bembicoides* Sands, 1995.**	None.	Zambia (Sands, 1998).	Lusaka (Type locality), in Lusaka Province.
	***Fulleritermes contractus* (Sjöstedt, 1913).**	*Coarctotermes brunneus* Noirot, 1955; *Eutermes contractus* Sjöstedt, 1913.	Congo-Zaire [Now Democratic Republic of Congo], Namibia, South Africa, Zambia, Zimbabwe (Bouillon and Mathot 1965, 1966; Coaton and Sheasby, 1973b; Nkunika, 1982; Sands, 1957; Sands 1965; Sands, 1998).	Southern Province.
	***Furculitermes soyeri* Emerson, 1960.**	None.	Congo-Zaire [Now, Democratic Republic of Congo], Zambia (Sands, 1998).	Chingola, Copperbelt Province.
	***Lepidotermes goliathi* (Williams, 1954).**	None.	Tanzania; Zambia; Zimbabwe (Uys, 1994).	Lusaka, in Lusaka Province.
	***Macrotermes bellicosus* (Smeathman, 1781).**	*Bellicositermes convexus* Grasse, 1937; *Termes bellicosus* Smeathman, 1781; *Termes bellicosus zambesiana* Van Boven, 1969; *Termes carboniceps* Sjöstedt, 1924; *Termes nigeriensis* Sjöstedt, 1911.	Angola, Cameroon, Central African Republic, Congo-Brazzaville, Congo-Zaire [Now, Democratic Republic of Congo], Eritrea, Ethiopia, Ghana, Guinea, Guinea-Bissau, Ivory Coast (Cote d'Ivoire), Kenya, Liberia, Malawi, Mauritania, Mozambique, Niger, Nigeria, Senegal, Sierra Leone, Somalia, Sudan, Tanzania, Togo, Uganda, Yemen, Zambia (Coaton, 1962; Mbata, 1995; Ruelle, 1970; Silvestri, 1912; Sjöstedt, 1926).	Lusaka, in Lusaka Province.
	***Macrotermes falciger* (Getstäecker, 1891). ***	*Macrotermes usutu* Fuller, 1922; *Termes falciger* Gerstacker, 1891; *Termes goliath* Sjöstedt, 1899; *Termes michelli* Rosen, 1912; *Termes swaziae* Fuller, 1915; *Tumulitermes kibonotensis* Sjöstedt, 1924.	Benin, Central African Republic, Congo-Zaire [Now, Democratic Republic of Congo], Ghana, Guinea, Kenya, Malawi, Mozambique, South Africa, Swaziland, Tanzania, Uganda, Zambia (Bouillon and Mathot, 1971; Coaton, 1962; Mbata, 1995; Nkunika, 1982, 1986; Ruelle et al., 1975a; Ruelle, 1970; Wood and Tomas, 1989)	Southern Province; Lusaka**, in Lusaka Province; Treetops** (Kafue National Park), in Northwestern Province; Ndola and Chingola, in Copperbelt Province; Mfuwe** and Chipata, in Eastern Province.
	***Macrotermes michaelseni* (Sjöstedt, 1914).**	*Macrotermes bellicosus kunenensis* Fuller, 1922; *Macrotermes bellicosus limpopoensis* Fuller, 1922; *Macrotermes bellicosus tonga* Fuller, 1927; *Termes* (*Termes*) *bellicosus mossambica* Hagen, 1858; *Termes* (*Termes*) *michaelseni* Sjöstedt, 1914.	Angola, Botswana, Kenya, Malawi, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia, Zimbabwe (Bouillon and Mathot, 1971; Mbata, 1995; Nkunika, 1982, 1986; Ruelle et al., 1975; Ruelle, 1970; Snyder, 1949a).	Southern Province; Lusaka, in Lusaka Province.
	***Macrotermes natalensis* (Haviland, 1898).**	*Macrotermes natalensis durbanensis* Fuller, 1927; *Macrotermes natalensis intermedius* Fuller, 1922; *Macrotermes natalensis transvaalensis* Fuller, 1922; *Termes natalensis* form *durbanensis* Fuller 1927; *Termes natalensis* form *intermedius* Fuller 1922 + 3.	Angola, Chad, Central African Republic, Congo-Brazzaville, Congo-Zaire, Eritrea, Ghana, Guinea, Guinea-Bissau, Ivory Coast (Côte d'Ivoire), Kenya, Liberia, Madagascar, Malawi, Mozambique, Namibia, Nigeria, Senegal, South Africa, Sudan, Tanzania, Togo, Uganda, Zambia, Zimbabwe (Bouillon and Mathot, 1971; Coaton, 1962; Mbata, 1995; Nkunika, 1982; Ruelle et al., 1975; Ruelle, 1970; Wood and Tomas, 1989).	Southern Province.
	***Macrotermes subhyalinus* (Rambur, 1842).**	*Bellicositermes bellicosus rex* Grasse and Noirot, 1961; *Bellicositermes jeanneli* Grasse, 1937; *Termes bellicosus sansibarita* Wasmann, 1897; *Termes subhyalinus* Rambur, 1842; *Termes tumulicola* Sjöstedt, 1899.	Angola, Benin, Burundi, Central African Republic, Chad, Congo-Zaire [Now, Democratic Republic of Congo], Ethiopia, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast (Côte d'Ivoire), Kenya, Liberia, Malawi, Mali, Mozambique, Namibia, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, Sudan, Tanzania, Togo, Uganda, Yemen, Zambia, Palaearctic Region — Oman, Saudi Arabia (Bouillon and Mathot, 1971; Mbata, 1995; Nkunika, 1982; Ruelle et al., 1975; Ruelle, 1970; Ruelle, 1975b).	Southern Province; Chipata District in Eastern Province; Chelstone, in Lusaka Province.
	***Macrotermes vatrialatus* (Sjöstedt, 1899).**	*Termes vitrialatus* Sjöstedt, 1899: *Termes imperator* Sjöstedt, 1913; *Termes waterbergi* Fuller, 1915; *Macrotermes schoutedeni* Sjöstedt, 1924; *Amplitermes mozambicanus* Sjöstedt, 1926 + 1.	Angola, Congo-Brazzaville, Congo-Zaire [Now, Democratic Republic of Congo], Malawi, Mozambique, Namibia, South Africa, Tanzania, Zambia, (Bouillon and Mathot, 1971; Mbata,1995; Nkunika 1982, 1986; Ruelle et al., 1975a; Ruelle, 1970).	Southern Province.
	***Megagnathotermes katangensis* Sjöstedt, 1927.**	None.	Zambia (Bouillon and Vincke, 1973c; Nkunika, 1982; Sands, 1998).	Southern Province.
	***Microcerotermes brachygnathus* Silvestri, 1914.**	None.	South Africa, Tanzania, Zambia, Zimbabwe (Krishna et al., 2016; Nkunika, 1986).	Lochinvar in Monze, in Southern Province.
	***Microcerotermes fuscotibialis* (Sjöstedt, 1896).**	None.	Angola, Cameroon, Congo-Zaire [Now, Democratic Republic of Congo], Gabon, Ghana, Guinea, Ivory Coast (Côte d'Ivoire), Nigeria, Senegal, Sierra Leone, Zambia (Livingstone National Museum Report, Zambia Collection, 2013).	Southern Province.
	***Microcerotermes nemoralis* Harris, 1954.**	None.	Tanzania, Zambia (Bouillon and Mathot, 1965; Nkunika, 1982).	Southern Province.
	***Microcerotermes parvus* (Haviland, 1898).**	None.	Angola, Cameroon, Congo-Brazzaville, Congo-Zaire [Now, Democratic Republic of Congo], Eritrea, Ethiopia, Gabon, Ghana, Ivory Coast, Kenya, Nigeria, Senegal, South Africa, Sudan, Tanzania, Uganda, Zambia (Livingstone National Museum Report, Zambia Collection, 2013).	Southern Province.
	***Microcerotermes solidus* Silvestri, 1912.**	None.	Angola, Cameroon, Congo-Zaire, Ghana, Guinea, Guinea-Bissau, Ivory Coast (Côte d'Ivoire), Nigeria, Senegal, Zambia (Livingstone National Museum Report, Zambia Collection, 2013).	Southern Province.
	***Microtermes albopartitus* (Sjöstedt, 1911).**	*Microtermes longiceps* Holmgren, 1913; *Termes albopartitus* Sjöstedt, 1911.	Cameroon, Congo-Zaire [Now, Democratic Republic of Congo], Malawi, South Africa, Tanzania, Zambia, Zimbabwe (Bacchus, 1997).	Lusaka, Lusaka Province.
	***Microtermes chomaensis* Bacchus, 1997.**	None.	Zambia (Bacchus, 1997).	Choma, in Southern Province.
	***Microtermes etiolatus* Fuller, 1922.**	None.	Mozambique, South Africa, Zambia (Bacchus, 1997).	Lusaka, in Lusaka Province.
	***Microtermes kasaiensis* (Sjöstedt, 1913).**	*Eutermes kasaiensis* Sjöstedt, 1913.	Congo-Zaire; Kenya; Malawi; Uganda. Zambia (Nkunika, 1982).	Southern Province.
	***Microtermes lounsburyi* Fuller, 1922.**	*Microtermes umfolozii* Fuller, 1922	Malawi, South Africa, Zambia, Zimbabwe (Bacchus, 1997).	Kabwe, Central Province.
	***Microtermes luteus* Harris, 1954.**	None.	Kenya, Malawi, Tanzania, Zambia (Krishna et al., 2016; Nkunika, 1982).	Southern Province.

Family	Scientific name	Synonym(s)	Distribution	Location in Zambia
	***Microtermes magnocellus* (Sjöstedt, 1915).**	*Termes* (*Microtermes*) *magnocellus* Sjöstedt, 1915.	Ethiopia, Tanzania, Malawi, Zambia (Bacchus, 1997; Krishna et al., 2016).	Lusaka, Lusaka Province.
	***Microtermes pamelae* Bacchus, 1997.**	None.	Zambia (Bacchus, 1997; Krishna et al., 2016).	Type locality, Mbala, in Northern Province.
	***Microtermes vadschaggae* (Sjöstedt, 1907).**	*Termes vadschaggae* Sjöstedt, 1907.	Ethiopia, Kenya, Malawi, Senegal, Tanzania, Zambia (Krishna et al, 2016; Nkunika, 1986).	Lochinvar, in Southern Province.
	***Mimeutermes binghami* Sands, 1968.**	None.	Kenya, Zambia (Bouillon and Mathot, 1971; Sands, 1998).	Roma in Lusaka (Type locality), in Lusaka Province.
	***Nitiditermes berghei* Emerson, 1960.**	None.	Congo-Zaire [Now Democratic Republic of Congo], Zambia (Krishna et al, 2016; Sands 1998).	Lusaka, in Lusaka Province; Chingola and Chililabombwe, in Copperbelt Province.
	***Odontotermes badius* (Haviland 1898).**	*Termes badius* Haviland, 1898; *Odontotermes badius badius* (Haviland, 1898).	Angola, Botswana, Cameroon, Congo-Zaire [Now, Democratic Republic of Congo], Ethiopia, Kenya, Malawi, Namibia, Somalia, South Africa, Swaziland, Tanzania, Uganda, Zambia, Zimbabwe (Krishna et al., 2016; Nkunika, 1982).	Southern Province.
	***Odontotermes flammifrons* (Sjöstedt, 1926).**	*Termes flammifrons* Sjöstedt, 1926.	Congo-Zaire [Now, Democratic Republic of Congo], Malawi, Sudan, Zambia (Bouillon and Mathot, 1965; Harris, 1960).	Lusaka, in Lusaka Province.
	***Odontotermes lacustris* Harris, 1960.**	None.	Malawi, Zambia (Bouillon and Mathot, 1965; Nkunika 1982, 1986; Wood and Tomas, 1989).	Type locality of this species is Abercorn [Now, Mbala - 08°50′S, 31°24′E] in Northern Province; Kalomo, Mazabuka, Monze, Lochinvar and Choma, in Southern Province.
	***Odontotermes latericius latericius* (Haviland, 1898).**	*Odontotermes latericius* (Haviland, 1898); *Termes latericius* Haviland, 1898.	Angola, Botswana, Congo-Zaire [Now Democratic Republic of Congo], Kenya, Malawi, Mozambique, Namibia, Senegal, South Africa, Sudan, Tanzania, Togo, Uganda, Zimbabwe, Zambia (Nkunika 1982, 1986; Silvestri, 1912; Sjöstedt, 1926; Wood and Tomas, 1989).	Southern Province.
	***Odontotermes transvaalensis* (Sjöstedt, 1902).**	*Termes transvaalensis* Sjöstedt, 1902; *Termes tubicola* Wasmann, 1902.	Botswana, Ethiopia, Kenya, South Africa, Tanzania, Uganda, Zambia, Zimbabwe (Krishna et al., 2016; Livingstone National Museum Report, Zambia Collection, 2013).	Southern Province.
	***Ovambotermes sylvaticus* Coaton, 1971.**	None.	Namibia, Zambia (Krishna et al., 2016; Sands, 1998).	Lusaka, Lusaka Province.
	***Pericapritermes gloveri* Harris, 1951.**	None.	Tanzania, Zambia (Bouillon and Mathot, 1965; Sands, 1998).	Kalambo Falls on south bank river [08°35′S, 31°13′E], in Northern Province.
	***Promirotermes massaicus* (Sjöstedt, 1907).**	*Eutermes massaicus* Sjöstedt, 1907.	Kenya; Tanzania; uganda; and Zambia (Krishna et al., 2016; Nkunika, 1982).	Southern Province.
	***Protermes minimus* Ruelle, 1971.**	None.	Angola, Congo-Zaire [Now, Democratic Republic of Congo], Guinea, Nigeria, Zambia (Ruelle, 1975a).	Lusaka, in Lusaka Province.
	***Protermes minutus* Grassé, 1937.**	*Termes minutus* Grassé, 1937.	Angola; Congo-Zaire; Gabon; Guinea; Ivory Coast (Cote d'Ivoire); Nigeria; Sierra Leone; Zambia (Krishna et al., 2016).	Lusaka, in Lusaka Province.
	***Protermes mwekerae* Ruelle, 1971.**	None.	Zambia (Krishna et al., 2016; Ruelle, 1975 a&b).	Type locality 24 km ex Kitwe-Dola Hill via Mwekera Forest Reserve. In Copperbelt Province of Zambia.
	***Pseudacanthotermes militaris militaris* (Hagen, 1858).**	*Acanthotermes militaris minor* Sjöstedt, 1913; *Termes* (*Termes*) *militaris* Hagen, 1858.	Angola, Benin, Cameroon, Central African Republic, Congo-Brazzaville, Congo-Zaire [Now, Democratic Republic of Congo], Equatorial Guinea, Ethiopia, Gabon, Ghana, Guinea, Ivory Coast (Côte d'Ivoire), Kenya, Malawi, Nigeria, Sierra Leone, South Africa, Tanzania, Togo, Uganda, Zambia, Zimbabwe (Coaton and Sheasby, 1977; Nkunika, 1982; Sjöstedt, 1926).	Southern Province.
	***Pseudacanthotermes spiniger* (Sjöstedt, 1900).**	*Acanthotermes spiniger kohli* Wasmann, 191; *Acanthotermes spiniger lujae* Wasmann, 1904; *Pseudacanthotermes spiniger maynei* Sjöstedt, 1926; *Pseudacanthotermes unsgaardi* Sjöstedt, 1926; *Termes* (*Acanthotermes*) *spiniger* Sjöstedt, 1900.	Angola, Cameroon, Central African Republic, Congo-Brazzaville, Congo-Zaire [Now, Democratic Republic of Congo], Ghana, Guinea, Ivory Coast (Côte d'Ivoire), Kenya, Nigeria, Sudan, Tanzania, Uganda, Zambia (Coaton and Sheasby, 1977; Nkunika, 1982; Wood and Tomas, 1989).	Southern Province.
	***Rhadinotermes coarctatus* (Sjöstedt, 1902).**	*Eutermes coarctatus* Sjöstedt, 1902.	Congo-Zaire [Now, Democratic Republic of Congo], Malawi, Namibia, South Africa, Swaziland, Tanzania, Zambia, Zimbabwe (Bouillon and Mathot, 1966; Coaton and Sheasby, 1974; Sands, 1965; Sands, 1998).	Kabwe, Central Province.
	***Spatulitermes coolingi* Coaton, 1971.**	None.	Namibia, Zambia (Sands, 1998).	Lusaka, in Lusaka Province.
	***Synacanthotermes trilobatus* Sjöstedt, 1926.**	*Synacanthotermes angolensis* Weidner, 1956; *Synacanthotermes heterodon trilobata* Sjöstedt, 1926.	Angola, Congo-Zaire [Now, Democratic Republic of Congo], Malawi, Zambia (Krishna et al., 2016; Sands, 1998).	Lusaka, Lusaka Province.
	***Synacanthotermes zanzibarensis* (Sjöstedt, 1915).**	*Te r m e s* (*Synacanthotermes*) *zanzibarensis* Sjöstedt, 1915.	Ethiopia, Kenya, Tanzania, Zambia (Livingstone National Museum Report, Zambia Collection, 2013).	Kitwe, Ndola and Chati in Copperbelt Province.
	***Termes boultoni* Coaton and Sheasby, 1978.**	*Termes kalaharicus* Irish, 1985: 111 [nomen nudum; name credited to Coaton].	Zambia, Zimbabwe (Nkunika, 1982; Sands, 1998).	Southern Province.
	***Thoracotermes lusingensis* Harris, 1958.**	None.	Angola, Congo-Zaire [Now, Democratic Republic of Congo], Zambia (Krishna et al., 2916; Sands, 1998).	Lusaka, Lusaka Province.
	***Trinervitermes bettonianus* (Sjöstedt, 1905).**	*Eutermes bettonianus* Sjöstedt, 1905; *Eutermes crassinasus* Sjöstedt, 1914; *Eutermes* (*Trinervitermes*) *ruficeps* Holmgren, 1913; *Eutermes segelli* Sjöstedt, 1907.	Congo-Zaire [Now, Democratic Republic of Congo], Kenya, Malawi, Mozambique, Tanzania, Uganda, Zambia, Zimbabwe (Bouillon and Mathot, 1966; Nkunika 1982, 1986; Sands 1957, 1965; Snyder, 1949).	Southern Province.
	***Trinervitermes dispar* (Sjöstedt, 1902).**	*Eutermes dispar* Sjöstedt, 1902; *Eutermes* (*Trinervitermes*) *erythreae* Holmgren, 1913; *Eutermes gemellus* Sjöstedt, 1902; *Eutermes grootfonteinsis* Sjöstedt, 1914; *Eutermes katangensis* Sjöstedt, 1913 + 3.	Congo-Zaire [Now, Democratic Republic of Congo], Eritrea, Ethiopia, Kenya, Malawi, Namibia, South Africa, Swaziland, Tanzania, Uganda, Zambia, Zimbabwe (Bouillon and Mathot 1965, 1966; Nkunika, 1982; Sands 1957, 1965).	Southern Province.
	***Trinervitermes gratiosus* (Sjöstedt, 1924).**	*Eutermes* (*Trinervitermes*) *carbo* Sjöstedt, 1924; *Eutermes* (*Trinervitermes*) *gratiosus* Sjöstedt, 1924.	Angola, Burundi, Congo-Zaire [Now, Democratic Republic of Congo], Kenya, Rwanda, Tanzania, Uganda, Zambia (Krishna et al., 2016; Nkunika, 1982, 1986).	Southern Province.
	***Trinervitermes occidentalis* (Sjöstedt, 1904).**	*Eutermes occidentalis* Sjöstedt, 1904; *Nasutitermes* (*Trinervitermes*) *bettonianus sulciceps* Emerson, 1928; *Nasutitermes* (*Trinervitermes*) *lutzi* Emerson, 1928; *Trinervitermes auriterrae* Sjöstedt, 1926; *Trinervitermes maudanicus* Sjöstedt, 1926.	Central African Republic, Congo-Zaire [Now, Democratic Republic of Congo], Ethiopia, Ghana, Guinea-Bissau, Ivory Coast (Cote d'Ivoire), Nigeria, Sierra Leone, Uganda, Zambia (Bouillon and Mathot, 1965, 1966; Krishna et al., 2016).	Lusaka, in Lusaka Province.
	***Trinervitermes rhodesiensis* (Sjöstedt, 1911)**	*Eutermes agricola* Sjöstedt, 1913; *Eutermes brutus* Sjöstedt, 1911; *Eutermes* (*Trinervitermes*) *diplacodes* Sjöstedt, 1924; *Eutermes* (*Trinervitermes*) *kalaharicus* Holmgren, 1913; *Eutermes* (*Trinervitermes*) *loubetsiensis* Sjöstedt, 1924 + 6.	Angola, Botswana, Central African Republic? Congo-Brazzaville, Congo-Zaire [Now, Democratic Republic of Congo], Namibia, South Africa, Tanzania, Zambia, Zimbabwe (Bouillon and Mathot, 1966; Nkunika, 1982; Sands, 1965).	Southern Province.
	***Unguitermes proclivifrons* Ruelle, 1973.**	None.	Zambia (Krishna et al., 2016; Ruelle, 1975).	Type locality, 30 km ex Kitwe-Dola via Mwekera Forest Reserve, Copperbelt Province of Zambia.

Table 3: Checklist of Blattodea of Zambia: Families Rhinotermitidae, Kalotermitidae and Hodotermitidae.

Family	Scientific name	Synonym(s)	Distribution	Location in Zambia
Superfamily BLATTOIDEA: Epifamily Termitoidae				
Rhinotermitidae	***Coptotermes amanii* (Sjöstedt, 1911).**	*Eutermes* (*Coptotermes*) *amanii* Sjostedt, 1911	Ethiopia, Kenya, Malawi, Somalia, South Africa (introduced from East Africa), Tanzania, Zambia, Zimbabwe (Krishna et al., 2016).	Lusaka, in Lusaka Province.
	***Schedorhinotermes lamanianus* (Sjöstedt, 1911).**	*Rhinotermes bequaertianus* Sjostedt, 1913; *Rhinotermes havilandi* Van Boven, 1969; *Rhinotermes lamanianus* Sjostedt, 1911; *Rhinotermes* (*Schedorhinotermes*) *lamanianus angulatus* Emerson, 1928; *Schedorhinotermes provisorius* Grasse, 1937 + 1.	Angola, Congo-Brazzaville, Congo-Zaire [Now, Democratic Republic of Congo], Ghana, Guinea, Ivory coast, Kenya, Malawi, Mozambique, Namibia, Nigeria, Sierra Leone, South Africa, Swaziland, Tanzania, Uganda, Zambia, Zimbabwe (Coaton and Sheasby, 1973b; Maiti, 2006; Nkunika, 1982).	Southern Province.
Kalotermitidae	***Bifiditermes sibayiensis* (Coaton, 1949).**	*Kalotermes sibayiensis* Coaton, 1949.	Namibia, South Africa, Swaziland, Tanzania, Zambia, Zimbabwe (Coaton and Seasby, 1980; Nkunika, 1982).	Southern Province.
Hodotermitidae	***Hodotermes mossambicus* (Hagen, 1853) *.**	*Hodotermes* (*Hodotermes*) *bloemfonteinsis* Sjöstedt, 1926; *Hodotermes braini* Fuller, 1915; *Hodotermes havilandi* Sharp, 1895; *Hodotermes karrooensis* Fuller, 1915; *Hodotermes macrothorax* Sjöstedt, 1914 + 6.	Angola, Botswana, Ethiopia, Kenya, Malawi, Mozambique, Namibia, South Africa, Tanzania, Uganda, Zambia (Krishna et al., 2016; Nkunika 1982, 1986; Pinhey, 1975; Sands, 1998).	Victoria Falls region in Southern Province; Kafue** Lusaka**and Kafue** and Lower Zambezi** National Parks, in Lusaka Province; Chisamba**, in Central Province.

Table 4. Checklist of Blattodea of Zambia: Family Blattellidae.

Family	Scientific name	Synonym(s)	Distribution	Location in Zambia
Superfamily BLABEROIDEA Saussure, 1864.				
Blattellidae (= Ectobiidae Wood Cockroaches)	***Anaplecta cincta cincta* Gerstaecker, 1883.**	*Anaplecta cincta* (Gerstaecker, 1883).	Angola, Democratic Republic of Congo, Gabon, Mozambique, South Africa, Tanzania, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014).	Chingola, in Copperbelt Province.
	***Blattella germanica* (Linnaeus, 1767). ***	*Blatta asiatica* (Pallas, 1773); *Blatta bivittata* Serville, 1838; Blatta daunca (Laxmann, 1769); *Blatta daurica* Laxmann, 1769; Blatta germanica Linnaeus, 1767 + 20.	Cosmopolitan [Asian origin]; The German cockroach is found throughout the world in association with humans. Cameroon, Congo-Brazzaville, Democratic Republic of Congo, Kenya, Madagascar, South Africa, Swaziland, Tanzania, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; Ministry of Environment and Natural Resources, 1998; Mbata, 1998; Plant Pests and Diseases Act. No. 13. 1994).	Lusaka** in Lusaka Province; Monze and Livingstone in the Southern Province; Ndola and Kitwe in Copperbelt Province; Solwezi** in Northwestern Province; Mongu in Western Province; Chipata in Eastern Province; Mansa in Luapula Province; Luwingu in Northern Province.
	***Blattella lobiventris* (Saussure, 1895).**	*Blatta lobiventris* Saussure, 1895; *Blatta madecassa* Saussure, 1895; *Blatta scioana* (Adelung, 1905); *Blattella pallidula* Werner, 1907; *Blattella schubotzi* Shelford, 1912 + 8.	Angola, Burkina Faso, Burundi, Cameroon, Congo-Brazzaville [= Republic of Congo], Democratic Republic of Congo, Equatorial Guinea, Ethiopia, Guinea, Ivory Coast, Kenya, Madagascar, Mozambique, Namibia, Rwanda, Sierra Leone, South Africa, Spanish Guinea, Sudan, Swaziland, Tanzania, Uganda, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Gorges, east of Victoria Falls and Livingstone, in Southern Province.
	***Burchellia neavei* Shelford, 1913.**	*Hemithyrsocera neavei* (Shelford, 1913).	Democratic Republic of Congo, Ghana, Zambia (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Chililabombwe, in Copperbelt Province.
	***Burchellia vinula* (Stal, 1856).**	*Blatta vinula* (Stal, 1856).	Angola, Democratic Republic of Congo, Mozambique, South Africa, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Chililabombwe, in Copperbelt Province.
	***Ectobius africanus* (Saussure, 1899).**	*Ectobius* (*Ectobius*) *africanus* Saussure, 1899.	Angola, Central African Republic, Democratic Republic of Congo, Ethiopia, Kenya, Malawi, Mozambique, Rwanda, South Africa, Sudan, Tanzania, Togo, Uganda, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Lusaka, in Lusaka Province.
	***Ectobius makalaka* Rehn, 1931.**	*Ectobius fernandesi* (Harz, 1975); *Ectobius ferrum-equinum* (Costa, 1866); *Ectobius helvetica* (Hagenbach, 1822); *Ectobius lapponicus picta* (Adelung, 1917); *Ectobius* (*Ectobius*) *makalaka* Rehn, 1931.	Malawi, Spain, Tanzania, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Mpika, in Muchinga Province; Kapiri Mposhi, in Central Province.
	***Matabelina backlundi* Princis, 1969.**	None.	Democratic Republic of Congo, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Lusaka, Lusaka Province.
	***Matabelina ectobioides* (Shelford, 1910).**	*Temnopteryx ectobioides* (Shelford, in Sjöstedt 1910)	Rwanda, Tanzania, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Kafue and Lusaka, in Lusaka Province.
	***Stayella abnormalis* (Roth, L. M., 1984).**	None.	Zambia (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Lusaka, in Lusaka Province.
	***Stayella bimaculata* (Gerstaecker, 1869).**	*Phyllodromia bimaculata* (Gerstaecker, 1869); *Symploce bimaculata* (Gerstaecker, 1869); *Symploce backlundi* Princis, 1963; *Symploce massaica* Princis, 1951.	Angola, Democratic Republic of Congo, Kenya, Mozambique, Tanzania, Zambia (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Mbala, in Northern Province.
	***Supella dimidiata* (Gerstaecker, 1869).**	*Aphlebia transvaaliensis* (Kirby, 1900); *Ceratinoptera dimidiata* Gerstaecker, 1869; *Ceratinoptera hottentotta* (Saussure, 1899); *Phyllodromia delta* Kirby, 1900; *Supella delta* (Kirby, 1900) + 5.	Angola, Botswana, Democratic Republic of Congo, Eritrea, Kenya, Malawi, Mozambique, Namibia, South Africa, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Kalabo, in Western Province; Kabwe, in Central Province.
	***Supella supellectilium* Serville, 1838. ***	*Blatta cubensis* Saussure, 1862; *Blatta extenuata* Walker, 1868; *Blatta incisa* Walker, 1868; *Blatta longipalpa* Fabricius, 1798; *Blatta phalerata* Saussure, 1863 + 8.	Algeria, Gambia, Namibia, South Africa, Sudan, Tanzania, Togo, Zambia (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Gorges**, east of Victoria Falls in Livingstone, Southern Province; Lower Zambezi valley, Lusaka Province.
	***Symploce incuriosa* (Saussure, 1899).**	*Ischnoptera incuriosa* (Saussure, 1899); *Ischnoptera pitmani* Hanitsch, 1929; *Ischnoptera uniramosa* Karny, 1908; *Phyllodromia trigonalis* Saussure, 1899; *Symploce pitmani* (Hanitsch, 1929); *Symploce trigonalis* (Saussure, 1899).	Botswana, Namibia, South Africa, Tanzania, Uganda, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Chingola, in Copperbelt Province.
	***Theganopteryx obscura* (Shelford, 1911).**	None.	Democratic Republic of Congo, Mozambique, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Chingola, in Copperbelt Province.
	***Theganopteryx rhodesiae* (Shelford, 1913).**	None.	Cameroon, Democratic Republic of Congo, Rwanda, Zambia (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Environs of Lake Bangweulu, in Luapula Province.

Biodiversity

Table 5. Checklist of Blattodea of Zambia: Blaberidae and Corydiidae.

Family	Scientific name	Synonym(s)	Distribution	Location in Zambia
Superfamily BLABEROIDEA Saussure, 1864.				
Blaberidae (Giant Cockroaches)	***Cyrtotria capucina* (Gerstaecker, 1869).**	*Agis basilewskyi* Princis, 1955; *Cyrtotria basilewskyi* Princis, 1955; *Cyrtotria somali* (Saussure & Zehntner, 1895); *Derocalymma capucina* (Gerstaecker, 1869); *Stenopilema somali* Saussure & Zehntner, 1895.	Democratic Republic of Congo, Djibouti, Ethiopia, Kenya, Rwanda, Somaliland [Now, Somalia], Tanzania, Tanzania (Zanzibar Island), Uganda, Zambia (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Samfya, in Luapula Province.
	***Derocalymma lampyrina* Gerstaecker, 1869.**	*Derocalymma bottegoiana* Saussure & Zehntner, 1895; *Derocalymma punctata* Saussure & Zehntner, 1895.	Angola, Cameroon, Central African Republic, Democratic Republic of Congo, Djibouti, Ethiopia, Kenya, Mozambique, Namibia, Somalia, South Africa, Sudan, Tanzania, Uganda, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Chirundu bridge, in Lusaka Province.
	***Derocalymma porcellio* Gerstaecker, 1869.**	*Derocalymma bipapilla* (Kirby, 1900); *Derocalymma erythreiana* Saussure & Zehntner, 1895; *Homalodemas bipapilla* Kirby, 1900.	Angola, Democratic Republic of Congo, Djibouti, Ethiopia, Kenya, Malawi, Mozambique, Somalia, Tanzania, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Kasama, in Northern Province.
	***Derocalymma silphoides* Bolívar, 1889.**	None	Angola, Botswana, Namibia, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Kafue, Lusaka Province.
	***Eustegasta poecila* (Schaum, 1853). ***	*Eustegasta obsoleta* Kirby, 1900; *Eustegasta rhodesiana* Princis, 1949; *Panchlora poecila* (Schaum, 1853)	Kenya, Malawi, Mozambique, Tanzania, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3; Ministry of Environment and Natural Resources, 1998; Mbata, 1998; Pinhey, 1975).	Victoria Falls Region at gorges**, east of Victoria Falls in Livingstone, Southern Province.
	***Gyna kazungulana* Giglio-Tos, 1907.**	None.	Zambia (Only) (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Kazungula (Type locality) in Southern Province.
	***Gyna maculipennis* (Schaum, 1853). ***	*Gyna fervida* (Saussure, 1864); *Gyna insignata* (Kirby, 1896); *Gyna vetula* Brunner von Wattenwyl, 1865; *Panchlora fervida* Saussure, 1864; *Panchlora lata* Walker, 1868 + 2.	Angola, Benin, Cameroon, Democratic Republic of Congo, Gambia, Ghana, Ivory Coast, Kenya, Mozambique, Nigeria, Senegal, Sierra Leone, Swaziland, Tanzania, Togo, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3; Ministry of Environment and Natural Resources, 1998; Mbata, 1998; Pinhey, 1975).	Victoria Falls Region, at gorges**, east of Victoria Falls in Livingstone, Southern Province; Kafue Riverside Motel (RIMO)**in Kafue, Lusaka Province.
	***Gynopeltis cryptospila* (Walker, 1868). ***	*Gynopeltis picta* Gerstaecker, 1869; *Polyphaga cryptospila* (Walker, F., 1868); *Polyphaga erythrospila* Saussure, 1893.	Kenya, Malawi, Mozambique, Tanzania, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Kafue**, in Lusaka Province.
	***Gynopeltis neavei* Shelford, 1909.**	None	Zambia (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Lusaka, in Lusaka Province.
	***Nauphoeta cinerea* (Olivier, 1789).**	*Blatta cinerea* (Olivier, 1789); *Blatta elegans* Eschscholtz, 1822; *Blatta gallica* Fabricius, 1793; *Nauphoeta bivittata* Burmeister, 1838; *Nauphoeta gallica* (Fabricius, 1793); *Nauphoeta grisea* Burmeister, 1838.	Caribbean islands, China, Ecuador, Great Britain, India, Indonesia, Mozambique, Netherlands, Swaziland, Sweden, Taiwan, Tanzania, Zambia (Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Lusaka, in Lusaka Province; Kabwe, in Central Province.
	***Phenacisma semialata* Shelford, 1909.**	None.	Mozambique, Tanzania, Zambia (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Chingola, in Copperbelt Province.
	***Platysilpha murina* (Walker, 1868).**	*Perisphaeria murina* (Walker, F., 1868).	Mozambique, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Mpika, in Muchinga Province.
	***Pseudocalolampra pardalina* (Walker, 1868).**	*Calolampra aptera* Schulthess, 1898; *Calolampra arborifera* Hanitsch, 1939; *Calolampra pardalina* (Walker, F., 1868); *Epilampra pardalina* Walker, F., 1868; *Pseudocalolampra aptera* (Schulthess, 1898) + 1.	Botswana, Democratic Republic of Congo, Djibouti, Ethiopia, Kenya, Mozambique, Namibia, Rwanda, Somalia, South Africa, Swaziland, Tanzania, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Chililabombwe, in Copperbelt Province.
	***Pseudogyna intermedia* Shelford, 1909.**	None.	Zambia (Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Lusaka, in Lusaka Province.
	***Rhyparobia maderae* (Fabricius, 1781).**	*Blatta maderae* (Fabricius, 1781); *Blatta maderensia* Jones, 1859; *Blatta major* Palisot de Beauvois, 1805; *Blatta tuberculata* Thunberg, 1810; *Leucophaea maderae* (Fabricius, 1781) + 6.	Brazil, Cameroon, Caribbean islands, Chile, Colombia, Democratic Republic of Congo, Ecuador, Madagascar, Mexico, Netherlands, Nigeria, Portugal, Spain, Sweden, Tanzania, USA, Zambia (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Chililabombwe, in Copperbelt Province.
Superfamily CORYDIOIDEA Saussure, 1864.				
Corydiidae (Sand cockroaches)	***Ergaula capensis* (Saussure, 1893).**	*Dyscologamia wollastoni* Kirby, 1909	Angola, Cameroon, Congo-Brazzaville, Democratic Republic of Congo, Kenya, Nigeria, Tanzania, Tanzania (Zanzibar Island), Uganda, Zambia, Zimbabwe (Catalogue of life, 2016; Beccaloni, 2014; IUCN Red List of Threatened Species. Version 2016-3).	Lusaka, Lusaka Province.

A total of 27 genera of cockroaches are reported to occur in Zambia (Tab. 6). They are represented by 43 species and three subspecies. None of the 43 species of cockroaches has yet been evaluated for the IUCN (2016) Red List.

There are 38 genera of termites known to occur in Zambia. These include 87 species and one subspecies (Table 7). *Odontotermes latericius latericius* (Haviland, 1898), the nominate subspecies of *Odontotermes latericius* (Haviland, 1898), was the only subspecies reported to occur in the country in the literature.

Similar to the situation of cockroaches known to occur in Zambia reported in this paper, none of these 87 species of termites has been evaluated for the IUCN red list of threatened species to date.

Table 6: Numbers of cockroaches (Order Blattodea) known to occur in Zambia.

Family	Number of Genera	Number of Species	Number of Subspecies
Blattidae	6	12	2
Blattellidae	9	15	1
Blaberidae	11	15	0
Corydiidae	1	1	0
TOTAL	**27**	**43**	**3**

Table 7: Numbers of termites (Order Blattodea) known to occur in Zambia.

Family	Number of Genera	Number of Species	Number of Subspecies
Termitidae	34	83	1
Rhinotermitidae	2	2	0
Kalotermitidae	1	1	0
Hodotermitidae	1	1	0
TOTAL	**38**	**87**	**1**

Table 8 presents the distribution of cockroaches and termites known to occur in Zambia by province. The province with the largest numbers of reported species and subspecies of both cockroaches and termites is the Southern Province. This is followed by Lusaka Province. Copperbelt Province is the third, while the least known province regarding these two groups of insects, is the Western Province. The occurrence of seven species of cockroaches and two species of termites in Zambia was confirmed during the biodiversity field surveys. The cockroach species were: *Blatta orientalis* (Linnaeus, 1758), *Periplaneta americana* (Linnaeus, 1758), *Blattella germanica* (Linnaeus, 1767), *Supella supellectilium* (Serville, 1838), *Eustegasta poecila* (Schaum, 1853), *Gyna maculipennis* (Schaum, 1853), and *Gynopeltis cryptospila* (Walker, 1868), while the termite species are *Macrotermes falciger* (Gerstäecker, 1891), and *Hodotermes mossambicus* (Hagen, 1853). Some cockroach specimens and particularly those of termites collected from the field are not known and not yet determined whether or not they are new species. The unknown termite specimens have also not yet been compared with preserved specimens in the Livingstone National Museum for identification.

Table 8. Numbers of species and subspecies of cockroaches and termites in Zambia by province.

#	PROVINCE	COCKROACHES (Order Blattodea: Superfamilies Blattoidea [Epifamily Blattoidae], Blaberoidea, and Corydioidea).	TERMITES (Order Blattodea: Superfamily Blattoidea: [Epifamily Termitoidae])
1	Central	5	6
2	Copperbelt	12	14
3	Eastern	2	2
4	Luapula	3	4
5	Lusaka	20	25
6	Muchinga	3	3
7	Northern	5	8
8	Northwestern	3	1
9	Southern	21	47
10	Western	3	0

Discussion

Cockroaches: Superfamilies Blattoidea (Epifamily Blattoidae), Blaberoidea, and Corydioidea

The 43 species and three subspecies of cockroaches found to occur in Zambia in this study are a very large number compared to the 11-cockroach species recorded in the country's first National Biodiversity Strategy and Action Plan (NBSAP1). This difference in number is not suprising, however, as the study in 1998 was done in one -month.

The numbers of genera (27), species (43) and subspecies (3) of cockroaches reported for Zambia in this paper, are comparable to those of other countries in the region of southern Africa. The Southern Africa region as a whole has a total of 48 genera and 175 species of cockroaches from the Blattidae, Blattellidae, and Blaberidae families (Marshall, 1989). The total number of cockroach species occurring in South Africa for all families represented in the country is 35 (Biodiversityadvisor.sanbi.org., 2018). Other countries in southern Africa have not yet published checklists of their termites.

In terms of conservation, however, when the 43 species of cockroaches reported for Zambia in this paper were subjected to the IUCN's test, it was discovered that none has ever been evaluated for the IUCN red list of threatened species. Thus, their conservation statuses are still not known. The preparation of checklists of the different plant and animal taxa occurring in a country is important for conservation and determining the IUCN status of a given species is important in that it helps a country prioritize which taxa need to be conserved at a given time.

It should be noted, however, that there is a high possibility that some species of cockroaches present in the country could have been missed in this study, as sampling occurred in a limited number of places not representing all ecosystems. It was not possible to visit all provinces in Zambia because of the cost of conducting biodiversity surveys in the country. The survey group was large, requiring the hiring of three 4x4 vehicles, two with trailers. Furthermore, most of the surveys were done during the dry season in the country, when there are fewer insects in the environment, as many are in cryptic stages such as aestivating eggs and other inconspicuous insect developmental stages. But the 43 -species identified in this study, as indicated earlier, can be considered the baseline number of cockroaches for the country.

Termites: Superfamily Blattoidea (Epifamily Termitoidae)

According to Ruelle (1989) there are 50 genera and 210 species of termites in southern Africa. Zambia's 38 genera and 87 species reported in this paper could indicate that many more species known to occur in other parts of the region could be present and are yet to be found and collected in the country. Many other southern Africa countries do not have checklists for their termites. Outside southern Africa however, the numbers of genera and species of termites in other African countries are comparable with what has been determined for Zambia in this study. In Ethiopia in northern Africa for example, there are 25 genera and 61 species of termites (Cowie et al. 1990).

Among the termites, reported to exist in Zambia, some are crop pests. For instance, *Macrotermes bellicosus* (Smeathman, 1781), *Macrotermes falciger* (Getstäecker, 1891), *Macrotermes michaelseni* (Sjöstedt, 1914), *Macrotermes natalensis* (Haviland, 1898), *Macrotermes subhyalinus* (Rambur, 1842) and *Macrotermes vatrialatus* (Sjöstedt, 1899), are polyphagous general feeders that occasionally damage a wide range of crops including; cotton, coconut, coffee, cocoa, clove, groundnuts, rice, sugarcane fruit trees and forest trees (Hill, 2008). *Odontotermes badius* (Haviland 1898) and *Odontotermes latericius* (Haviland, 1898), also polyphagous feeders, attack a range of crops both as seedlings and as grown plants such as sugarcane, cotton and tea. They also destroy the wood of buildings. *Pseudacanthotermes militaris militaris* (Hagen, 1858), the so-called sugarcane termite, not only attacks sugarcane but also destroys bamboo stuctures

Biodiversity

including fences. *Hodotermes mossambicus* (Hagen, 1853), the harvester termite, attacks various grass species including maize and also impacts cotton.

For Zambia, other parts of tropical Africa and someparts of the tropical world, however, classifying these insects as pests is questionable. The term pest has the connotation that an organism in question is not beneficial to man. Some of the so-called termite pests especially the Macrotermes species mentioned above are edible (Mbata, 1995). Many ethnic groups in Zambia, tropical Africa and the tropical world, consume these insects so the species are beneficial to these people (Mbata, 1995). In Zambia the *Macrotermes* species are delicacies for both rural and urban communities. Alates of the species are collected during their nuptial flights that occur at the start of the rainy season in the country (November to March) and consumed as snacks and/or relish.

Only 36 species of termites were reported to occur in Zambia in the NBSAP1 (Chidumayo & Aongola, 1998; Mbata, 1998). This number has now risen to 87. Nevertheless, none of the 87 species and the one subspecies of termites found in Zambia has been evaluated for their IUCN conservation status. Again, an immediate question that comes to mind is, why conserve organisms some of which are pests to man? The answer is that any given organism on earth is essential to the normal functioning of of the planet's ecosystem(s).

Nkunika (1982) reported the presence of 41 species of termites in the Southern Province of Zambia alone. The species were grouped in 27 genera. He reported that the distribution of the termite species in the province was related to rainfall and the distribution of vegetation zones. Again, as stated in the cockroach section above, the actual number of termite species in Zambia is likely to be higher than the 87 found in this study. More work is required to ascertain this but in the mean time, the number 87 serves as a baseline for the future study of termite diversity in the country.

Finally, the intention of the author is to describe those cockroach and termite species that will be determined to be new species from specimen samples collected in various parts of the country in this study. For the purposes of this study, though the numbers of species of both cockroaches and termites found to have been reported to occur in Zambia in the literature and the few of those that were confined to occur in the country through the field surveys, are thought to be enough to serve as baseline data for the biodiversity of the two groups of insects in the country for future conservation programmes of the groups and further research.

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References

Bacchus, S. (1997) *Microtermes* in East Africa (Isoptera: Termitidae: Macrotermitinae). *Bulletin of the Natural History Museum, Entomology*, **66**, 123–171.

Biodiversityadvisor.sanbi.org. (2018) Isoptera checklist. *biodiversityadvisor.sanbi.org/wp-content/uploads/2014/08/Insecta-Isoptera.xlsx*

Bouillon, A. (1958) Les termites du Katanga. *Naturalistes Belges*, **39**, 198–208.

Bouillon, A. & Mathot, G. (1965) Quel est ce termite africain? *Zooleo (Kinshasa)*, **1**, 1–115.

Bouillon, A. & Mathot, G. (1966) Quel est ce termite africain? *Zooleo (Kinshasa)*, **1**, 1–23.

Bouillon, A. & Mathot, G. (1971) Quel est ce termite africain? *Zooleo (Kinshasa)*, **1**, 1–48.

Bouillon, A. & Vincke, P.P. (1973) *Megagnathotermes* Silvestri (Isoptera Termitinae): valvules entériques, révision des soldats, morphotype nouveau, comparaison avec *Cubitermes* et *Ophiotermes. Revue de Zoologie et de Botanique Africaines*, **87**, 764–774.

Catalogue of life (2016). http://www.catalogueoflife.org/col/details/species/id/

Chidumayo, E.N. & Aongola, L. (1998) *Zambia biodiversity strategy and action plan: the country report*. IUCN, Lusaka.

Coaton, W.G.H. (1962) The origin and development of massive, vegetated termite hills in northern Rhodesia. African Wild Life, **16**, 159–166.

Coaton, W.G.H. & Sheasby, J.L. (1973a) National survey of the Isoptera of southern Africa. 2. The genus *Schedorhinotermes* Silvestri (Rhinotermitidae). *Cimbebasia (Series A)*, **3**, 10–17.

Coaton, W.G.H. & Sheasby, J.L. (1973b) National survey of the Isoptera of southern Africa. 4. Te genus *Fulleritermes* Coaton (Termitidae: Nasutitermitinae). *Cimbebasia (Series A)*, **3**, 29–38.

Coaton, W.G.H. & Sheasby, J.L. (1974) National survey of the Isoptera of southern Africa. 5. The genus *Rhadinotermes* Sands (Termitidae: Nasutitermitinae). *Cimbebasia (Series A)* **3**, 39–45.

Coaton, W.G.H. & Sheasby, J.L. (1975) National survey of the Isoptera of southern Africa. 9. The genus *Ancistrotermes* Silvestri (Termitidae: Macrotermitinae). *Cimbebasia (Series A)*, **3**, 95–104.

Coaton, W.G.H. & Sheasby, J.L. (1977) National survey of the Isoptera of southern Africa. 13. The genus *Pseudacanthotermes* Sjostedt (Termitidae: Macrotermitinae). Cimbebasia (Series A), **3**, 183–205.

Coaton, W.G.H. & Sheasby, J.L. (1980) National survey of the Isoptera of southern Africa. 18. The genus *Bifiditermes* Krishna (Kalotermitidae). *Entomology Memoir, Department of Agricultural and Technical Services (South Africa)*, **53**, 1–13.

Cowie, R.H., Wood, TG., Barnett, E.A., Sands, W.A. & Black, H.I.J. (1990) A checklist of the termites of Ethiopia with a review of their biology, distribution and pest status. African Journal of Ecology, **28**, 21–33.

Davies, D.H. (1971) *Zambia in maps*. University of London Press Ltd., St Paul's House, London.

Emerson, A.E. (1928) Termites of the Belgian Congo and the Cameroon. *Bulletin of the American Museum of Natural History*, **57**, 401–574.

Harris, W.V. (1951) Further records of East African termites. *Proceedings of the Royal Entomological Society of London, Series B, Taxonomy*, **20**, 25–28.

Harris, W.V. (1960) Further records of East African termites—III. *Proceedings of the Royal Entomological Society of London, Series B, Taxonomy*, **29**, 17–21.

Harris, W.V. (1961) *Termites: their recognition and control*. Longmans, Green and Co., London.

Harris, W.V. (1966) The genus *Ancistrotermes* (Isoptera). *Bulletin of the British Museum (Natural History), Entomology*, **18**, 1–20.

Hill, D.S. (2008) *Pests of crops in warmer climates and their control*. Springer, Netherlands.

Hocking, B. (1965) Notes on some African termites. Proceedings of the Royal Entomological Society of London, Series A, General Entomology, **40**, 83–87.

International Union for Conservation of Nature (IUCN) (2016) red list of threatened species. Version 2016-3**.** www.iucnredlist.org.

Krishna, K., Grimaldi, D.A., Krishna, V. & Engel, M.S. (2013) *Treatise on the Isoptera of the world. Bulletin of the American Museum of Natural History*, no. 377. 7 vols. http://hdl.handle.net/2246/6430

Livingstone National Museum, (2013) Report. -*Insect Collection Register*. Livingstone National Museum, Natural History Department, Livingstone, Zambia.

Maiti, P.K. (2006) A taxonomic monograph on the world species of termites of the family Rhinotermitidae (Isoptera: Insecta). *Memoirs of the Zoological Survey of India*, **20**, 1–272.

Marshall, J. (1989) 5: Order Blattodea (cockroaches). *Insects of southern Africa* (ed by C.H. Scholtz, and E. Holm. 1989), pp. 49 -52. -Butterworths Professional Publishers (Pty) Ltd., Durban, South Africa.

Mbata, K.J. (1995) Traditional uses of Arthropods in Zambia: I. The food insects. *The Food Insects Newsletter*, **8**, 5 -7, 9.

Mbata, K.J. (1998) *Country study for Zambia National Biodiversity Strategy and Action Plan (BSAP): invertebrate component*. Prepared on behalf of IUCN – The World Conservation Union, Zambia Country Office, and the Ministry of Environment and Natural Resources (MENR), Lusaka.

Ministry of Environment and Natural Resources (MENR) (1998) *Zambia Biodiversity Strategy and Action Plan - the country study*. MENR, Lusaka.

Nkunika, P.O.Y. (1982) The termites of southern Zambia: their distribution in relation to vegetation zones. *Zambia Museums Journal*, **6**, 112–117.

Nkunika, P.O.Y. (1986) An ecological survey of the termites (Isoptera) of Lochinvar National Park, Zambia. *Journal of the Entomological Society of Southern Africa*, **49**, 45–53.

Pinhey, E.C.G. (1961) Dragonflies (Odonata) of Central Africa. *Occasional Papers, Rhodes-Livingstone Museum*, **14**, 1-97.

Pinhey, E. (1975) Chapter 14: Insects. *Mosi-oa-Tunya: a handbook to the Victoria Falls Region*. (ed. By D.W. Phillipson), pp. 201-218 Longman, Harare.

Pinhey, E. & Loe, I. (1973) *A guide to the insects of Zambia*. Anglo American Corporation (Central Africa) Ltd., Lusaka, Zambia.

Pinhey, E. & Loe, I. (1977) *A guide to the butterflies of Zambia*. Anglo American Corporation (Central Africa) Ltd., Lusaka, Zambia.

Plant Pests and Diseases Act, no. 13 (1994) Government of the Republic of Zambia. Government Printers, Lusaka.

Pratt, D. H. (2017) *Cockrooaches: pictorial key to some common species*. https://www.cdc.gov/nceh/ehs/docs/pictorial_keys/cockroaches.pdf

Ruelle, J.E. (1970) A revision of the termites of the genus *Macrotermes* from the Ethiopian region (Isoptera: Termitidae). Bulletin of the British Museum (Natural History), Entomology, **24**, 363–444.

Ruelle, J.E. (1975a) The genus *Protermes* (Isoptera: Termitidae): description of imago caste and new records from central Africa. *Journal of the Entomological Society of Southern Africa*, **38**, 155–163.

Ruelle, J.E. (1975b) Type specimens of Isoptera in the National Collection of Insects, Pretoria. *Entomology Memoir, Department of Agricultural and Technical Services (South Africa)*, **45**, 1–22.

Ruelle, J.E. (1979) National survey of the Isoptera of southern Africa. 16. A revision of the genus *Allodontermes* Silvestri from the Ethiopian region (Termitidae: Macrotermitinae). *Entomology Memoir, Department of Agricultural and Technical Services* (South Africa), **49**, 1–25.

Ruelle, J.E. (1989) 6: Order Isoptera (Termites). *Insects of Southern Africa* (ed. by C.H. Scholtz and E. Holm), pp. 53 -61. Butterworths Professional Publishers (Pty) Ltd., Durban, South Africa.

Ruelle, J.E., Coaton, W.G.H. & Sheasby, J.L. (1975) National survey of the Isoptera of southern Africa. 8. The genus *Macrotermes* Holmgren (Termitidae: Macrotermitinae). *Cimbebasia (Series A)*, **3**, 73–94.

Sands, W.A. (1957) A revision of the East African Nasutitermitinae (Isoptera). *Bulletin of the British Museum (Natural History), Entomology*, **5**, 1–28.

Sands, W.A. (1959) A revision of the termites of the genus *Amitermes* from the Ethiopian region (Isoptera, Termitidae, Amitermitinae). *Bulletin of the British Museum (Natural History), Entomology*, **8**, 129–156.

Sands, W.A. (1965) A revision of the termite subfamily Nasutitermitinae (Isoptera, Termitidae) from the Ethiopian region. *Bulletin of the British Museum (Natural History), Entomology (suppl.)*, **4**, 1–172.

Sands, W.A. (1972) The soldierless termites of Africa (Isoptera: Termitidae). *Bulletin of the British Museum (Natural History), Entomology (suppl.)*, **18**, 1–244.

Sands, W.A. (1992) The termite genus *Amitermes* in Africa and the Middle East. *Natural-Resources Institute Bulletin*, **51**, 1–140.

Sands, W.A. (1998) *The identification of worker castes of termite genera from soils of Africa and the Middle East*. CAB International, Wallingford, UK.

Silvestri, F. (1912) Termiti raccolte da S.A.R. la Duchessa d'Aosta nelle regione dei grandi laghi dell'Africa equatoriale. *Annuario del Museo Zoologico della R. Universita di Napoli (n.s.)*, **3**, 1–5.

Sjöstedt, Y. (1926) Revision der Termiten Afrikas. 3. Monographie. Kungliga Svenska Vetenskaps-Akademiens Handlingar **3**, 1–419.

Snyder, T.E. (1949) Catalog of termites (Isoptera) of the world. Smithsonian Miscellaneous Collections, **112**, 1–490.

South African National Biodiversity Institute (SANBI) (2018) *South African animal checklist*. http://biodiversityadvisor.sanbi.org/wp-content/uploads/2016/06/2016_04_13-animal-checklist.pdf

Uys, V.M. (1994) A systematic revision of the genus *Lepidotermes* Sjostedt (Isoptera: Termitidae). *Entomology Memoir, Department of Agricultural and Technical Services (South Africa)*, **90**, 1–53.

Victor, H.W. (1941) Termites in East Africa: field key and distribution (by territories). *East African Agricultural Journal*, **6**, 201-205. **Published online,** 06 Jan 2016.

Williams, R.M.C. (1966) The East African termites of the genus *Cubitermes* (Isoptera: Termitidae). Transactions of the Royal Entomological Society of London, **118**, 73–118.

Wood, T.G. & Thomas, R.J. (1989) The mutualistic association between Macrotermitinae and Termitomyces. *Insect-fungus interactions; 14th symposium of the Royal Entomological Society of London in collaboration with the British Mycological Society* (ed. by N. Wilding, N.M. Collins, P.M. Hammond, and J.F. Webber), pp. 6–17, 69–92. Academic Press, New York.

Worldatlas.com (2018) Environment: ecological regions of Zambia. https://www.worldatlas.com/articles/ecological-regions-of-zambia.html

References [CrossRef]

Bacchus, S. (1997) *Microtermes* in East Africa (Isoptera: Termitidae: Macrotermitinae). *Bulletin of the Natural History Museum, Entomology*, **66**, 123–171.

Biodiversityadvisor.sanbi.org. (2018) Isoptera checklist. *biodiversityadvisor.sanbi.org/wp-content/uploads/2014/08/Insecta-Isoptera.xlsx*

Bouillon, A. (1958) Les termites du Katanga. *Naturalistes Belges*, **39**, 198–208.

Bouillon, A. & Mathot, G. (1965) Quel est ce termite africain? *Zooleo (Kinshasa)*, **1**, 1–115.

Bouillon, A. & Mathot, G. (1966) Quel est ce termite africain? *Zooleo (Kinshasa)*, **1**, 1–23.

Bouillon, A. & Mathot, G. (1971) Quel est ce termite africain? *Zooleo (Kinshasa)*, **1**, 1–48.

Bouillon, A. & Vincke, P.P. (1973) *Megagnathotermes* Silvestri (Isoptera Termitinae): valvules entériques, révision des soldats, morphotype nouveau, comparaison avec *Cubitermes* et *Ophiotermes*. *Revue de Zoologie et de Botanique Africaines*, **87**, 764–774.

Catalogue of life (2016). http://www.catalogueoflife.org/col/details/species/id/

Chidumayo, E.N. & Aongola, L. (1998) *Zambia biodiversity strategy and action plan: the country*

report. IUCN, Lusaka.

Coaton, W.G.H. (1962) The origin and development of massive, vegetated termite hills in

northern Rhodesia. African Wild Life, **16**, 159–166.

Coaton, W.G.H. & Sheasby, J.L. (1973a) National survey of the Isoptera of southern Africa. 2. The genus *Schedorhinotermes* Silvestri (Rhinotermitidae). *Cimbebasia (Series A)*, **3**, 10–17.

Coaton, W.G.H. & Sheasby, J.L. (1973b) National survey of the Isoptera of southern Africa. 4. Te genus *Fulleritermes* Coaton (Termitidae: Nasutitermitinae). *Cimbebasia (Series A)*, **3,** 29–38.

Coaton, W.G.H. & Sheasby, J.L. (1974) National survey of the Isoptera of southern Africa. 5. The genus *Rhadinotermes* Sands (Termitidae: Nasutitermitinae). *Cimbebasia (Series A)* **3**, 39–45.

Coaton, W.G.H. & Sheasby, J.L. (1975) National survey of the Isoptera of southern Africa. 9. The genus *Ancistrotermes* Silvestri (Termitidae: Macrotermitinae). *Cimbebasia (Series A)*, **3**, 95–104.

Coaton, W.G.H. & Sheasby, J.L. (1977) National survey of the Isoptera of southern Africa. 13. The genus *Pseudacanthotermes* Sjostedt (Termitidae: Macrotermitinae). Cimbebasia (Series A), **3**, 183–205.

Coaton, W.G.H. & Sheasby, J.L. (1980) National survey of the Isoptera of southern Africa. 18. The genus *Bifiditermes* Krishna (Kalotermitidae). *Entomology Memoir, Department of Agricultural and Technical Services (South Africa)*, **53**, 1–13.

Cowie, R.H., Wood, TG., Barnett, E.A., Sands, W.A. & Black, H.I.J. (1990) A checklist of the termites of Ethiopia with a review of their biology, distribution and pest status. African Journal of Ecology, **28**, 21–33. CrossRef

Davies, D.H. (1971) *Zambia in maps*. University of London Press Ltd., St Paul's House, London.

Emerson, A.E. (1928) Termites of the Belgian Congo and the Cameroon. *Bulletin of the American Museum of Natural History*, **57**, 401–574.

Harris, W.V. (1951) Further records of East African termites. *Proceedings of the Royal Entomological Society of London, Series B, Taxonomy*, **20**, 25–28. CrossRef

Harris, W.V. (1960) Further records of East African termites—III. *Proceedings of the Royal Entomological Society of London, Series B, Taxonomy*, **29**, 17–21. CrossRef

Harris, W.V. (1961) *Termites: their recognition and control*. Longmans, Green and Co., London.

Harris, W.V. (1966) The genus *Ancistrotermes* (Isoptera). *Bulletin of the British Museum (Natural History), Entomology*, **18**, 1–20.

Hill, D.S. (2008) *Pests of crops in warmer climates and their control*. Springer, Netherlands. CrossRef

Hocking, B. (1965) Notes on some African termites. Proceedings of the Royal Entomological Society of London, Series A, General Entomology, **40**, 83–87.

International Union for Conservation of Nature (IUCN) (2016) red list of threatened species. Version 2016-3**.** www.iucnredlist.org.

Krishna, K., Grimaldi, D.A., Krishna, V. & Engel, M.S. (2013) *Treatise on the Isoptera of*

the world. Bulletin of the American Museum of Natural History, no. 377. 7 vols. http://hdl.handle.net/2246/6430

Livingstone National Museum, (2013) Report. -*Insect Collection Register*. Livingstone National Museum, Natural History Department, Livingstone, Zambia.

Maiti, P.K. (2006) A taxonomic monograph on the world species of termites of the family Rhinotermitidae (Isoptera: Insecta). *Memoirs of the Zoological Survey of India*, **20**, 1–272.

Marshall, J. (1989) 5: Order Blattodea (cockroaches). *Insects of southern Africa* (ed by C.H. Scholtz, and E. Holm. 1989), pp. 49 -52. -Butterworths Professional Publishers (Pty) Ltd., Durban, South Africa.

Mbata, K.J. (1995) Traditional uses of Arthropods in Zambia: I. The food insects. *The Food*

Insects Newsletter, **8**, 5 -7, 9.

Mbata, K.J. (1998) *Country study for Zambia National Biodiversity Strategy and Action Plan (BSAP): invertebrate component*. Prepared on behalf of IUCN – The World Conservation Union, Zambia Country Office, and the Ministry of Environment and Natural Resources (MENR), Lusaka.

Ministry of Environment and Natural Resources (MENR) (1998) *Zambia Biodiversity Strategy and Action Plan - the country study*. MENR, Lusaka.

Nkunika, P.O.Y. (1982) The termites of southern Zambia: their distribution in relation to vegetation zones. *Zambia Museums Journal*, **6**, 112–117.

Nkunika, P.O.Y. (1986) An ecological survey of the termites (Isoptera) of Lochinvar National

Park, Zambia. *Journal of the Entomological Society of Southern Africa*, **49**, 45–53.

Pinhey, E.C.G. (1961) Dragonflies (Odonata) of Central Africa. *Occasional Papers, Rhodes-Livingstone Museum*, **14**, 1-97.

Pinhey, E. (1975) Chapter 14: Insects. *Mosi-oa-Tunya: a handbook to the Victoria Falls Region*. (ed. By D.W. Phillipson), pp. 201-218 Longman, Harare.

Pinhey, E. & Loe, I. (1973) *A guide to the insects of Zambia*. Anglo American Corporation (Central Africa) Ltd., Lusaka, Zambia.

Pinhey, E. & Loe, I. (1977) *A guide to the butterflies of Zambia*. Anglo American Corporation (Central Africa) Ltd., Lusaka, Zambia.

Plant Pests and Diseases Act, no. 13 (1994) Government of the Republic of Zambia.

Government Printers, Lusaka.

Pratt, D. H. (2017) *Cockrooaches: pictorial key to some common species*. https://www.cdc.gov/nceh/ehs/docs/pictorial_keys/cockroaches.pdf

Ruelle, J.E. (1970) A revision of the termites of the genus *Macrotermes* from the Ethiopian region (Isoptera: Termitidae). Bulletin of the British Museum (Natural History), Entomology, **24**, 363–444. CrossRef

Ruelle, J.E. (1975a) The genus *Protermes* (Isoptera: Termitidae): description of imago caste and new records from central Africa. *Journal of the Entomological Society of Southern Africa*, **38**, 155–163.

Ruelle, J.E. (1975b) Type specimens of Isoptera in the National Collection of Insects, Pretoria. *Entomology Memoir, Department of Agricultural and Technical Services (South Africa)*, **45**, 1–22.

Ruelle, J.E. (1979) National survey of the Isoptera of southern Africa. 16. A revision of the genus

Allodontermes Silvestri from the Ethiopian region (Termitidae: Macrotermitinae). *Entomology Memoir, Department of Agricultural and Technical Services* (South Africa), **49**, 1–25.

Ruelle, J.E. (1989) 6: Order Isoptera (Termites). *Insects of Southern Africa* (ed. by C.H. Scholtz and E. Holm), pp. 53 -61. Butterworths Professional Publishers (Pty) Ltd., Durban, South Africa.

Ruelle, J.E., Coaton, W.G.H. & Sheasby, J.L. (1975) National survey of the Isoptera of southern Africa. 8. The genus *Macrotermes* Holmgren (Termitidae: Macrotermitinae). *Cimbebasia (Series A)*, **3**, 73–94.

Sands, W.A. (1957) A revision of the East African Nasutitermitinae (Isoptera). *Bulletin of the British Museum (Natural History), Entomology*, **5**, 1–28. CrossRef

Sands, W.A. (1959) A revision of the termites of the genus *Amitermes* from the Ethiopian region

(Isoptera, Termitidae, Amitermitinae). *Bulletin of the British Museum (Natural History), Entomology*, **8**, 129–156.

Sands, W.A. (1965) A revision of the termite subfamily Nasutitermitinae (Isoptera, Termitidae) from the Ethiopian region. *Bulletin of the British Museum (Natural History), Entomology (suppl.)*, **4**, 1–172.

Sands, W.A. (1972) The soldierless termites of Africa (Isoptera: Termitidae). *Bulletin of the British Museum (Natural History), Entomology (suppl.)*, **18**, 1–244.

Sands, W.A. (1992) The termite genus *Amitermes* in Africa and the Middle East. *Natural*

Resources Institute Bulletin, **51**, 1–140.

Sands, W.A. (1998) *The identification of worker castes of termite genera from soils of Africa and the Middle East*. CAB International, Wallingford, UK.

Silvestri, F. (1912) Termiti raccolte da S.A.R. la Duchessa d'Aosta nelle regione dei grandi laghi dell'Africa equatoriale. *Annuario del Museo Zoologico della R. Universita di Napoli (n.s.)*, **3**, 1–5.

Sjöstedt, Y. (1926) Revision der Termiten Afrikas. 3. Monographie. Kungliga Svenska Vetenskaps-Akademiens Handlingar **3**, 1–419.

Snyder, T.E. (1949) Catalog of termites (Isoptera) of the world. Smithsonian Miscellaneous Collections, **112**, 1–490.

South African National Biodiversity Institute (SANBI) (2018) *South African animal checklist*. http://biodiversityadvisor.sanbi.org/wp-content/uploads/2016/06/2016_04_13-animal-checklist.pdf

Uys, V.M. (1994) A systematic revision of the genus *Lepidotermes* Sjostedt (Isoptera: Termitidae). *Entomology Memoir, Department of Agricultural and Technical Services (South Africa)*, **90**, 1–53.

Victor, H.W. (1941) Termites in East Africa: field key and distribution (by territories).

East African Agricultural Journal, **6**, 201-205. Published online, 06 Jan 2016. CrossRef

Williams, R.M.C. (1966) The East African termites of the genus *Cubitermes* (Isoptera: Termitidae). Transactions of the Royal Entomological Society of London, **118**, 73–118. CrossRef

Wood, T.G. & Thomas, R.J. (1989) The mutualistic association between Macrotermitinae and Termitomyces. *Insect-fungus interactions; 14th symposium of the Royal Entomological Society of London in collaboration with the British Mycological Society* (ed. by N. Wilding, N.M. Collins, P.M. Hammond, and J.F. Webber), pp. 6–17, 69–92. Academic Press, New York. CrossRef

Worldatlas.com (2018) Environment: ecological regions of Zambia.

https://www.worldatlas.com/articles/ecological-regions-of-zambia.html

Biodiversity

Diversity patterns of woody vegetation of Kgatleng District, Botswana

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Abstract: Vegetation assessments have intensified around the globe to document plant diversity in the wake of climatic shifts and local environmental changes. Botswana also recognises the value of documenting plant diversity, and in this study we present the results of a vegetation survey of Kgatleng District. Between November 2013 and December 2016 we assessed tree species abundance on 77 plots sized 20 m × 50 m. Vegetation classification resulted in the identification of five woody plant communities: Terminalia sericea–Maytenus tenuispina, Dichrostachys cinerea–Combretum apiculatum, Combretum zeyheri–Vachellia tortilis, Senegalia erubescens–Senegalia mellifera, and Grewia flava–Rhigozium brevispinosum. One-way analysis of variance indicated that species richness was not different among the five plant communities, nor was tree density. We furthermore provide a vegetation map of the district based on supervised classification of Landsat 8 imagery.

Resumo: Estudos de vegetação intensificaram em todo o mundo, de modo a documentar a diversidade de plantas na sequência das alterações climáticas e de mudanças ambientais locais. O Botswana também reconhece o valor de documentar a diversidade de plantas e, neste estudo, apresentamos os resultados do levantamento da vegetação do Districto de Kgatleng. Entre Novembro de 2013 e Dezembro de 2016, avaliámos a abundância de espécies de árvores em 77 parcelas de 20 m × 50 m. A classificação da vegetação resultou na identificação de cinco comunidades de plantas lenhosas: *Terminalia sericea–Maytenus tenuispina, Dichrostachys cinerea–Combretum apiculatum, Combretum zeyheri–Vachellia tortilis, Senegalia erubescens–Senegalia mellifera*, *e Grewia flava–Rhigozium brevispinosum.* A análise da variância a um factor indicou que nem a riqueza específica, nem a densidade de árvores, eram diferentes entre as cinco comunidades de plantas. Fornecemos ainda um mapa da vegetação do districto baseado na classificação supervisionada de imagens de Landsat 8.

Introduction

Botswana, like most southern African countries, comprises expansive areas of savanna woodlands. Kgatleng District lies within the woodland and thorn bush savanna ecosystems. These ecosystems provide browse for domestic and wild animals, habitat cover for wild animals, wood products, and traditional medicines, among other uses. The diversity of ecosystems is integral to rural livelihoods, as they use veld products to sustain themselves. As such, effective management of savannas requires proper knowledge and documentation of vegetation types and species composition (Moore & Attwell, 1999).

Bush encroachment threatens the ecological integrity of savanna ecosystems and is of concern in southern Africa (Trollope, 1980; Skarpe 1990; Ward, 2005; Britz & Ward, 2007) and Botswana (Rhode et al., 2006), as it reduces diversity of vegetation. A number of causal drivers to changes in vegetation composition have been proposed, ranging from low rainfall to support grass growth, overgrazing, reduced fire frequency favouring woody plant establishment (Kgosikoma et al., 2012) and climatic shifts (O'Connor et al., 2014). To that end, environmentally friendly and sustainable methods of farming observing correct rangeland stocking rates have been advocated for in Botswana (Kgosikoma et al., 2012).

Species such as *Dichrostachys cinerea* can affect the development of other woody vegetation (Mudzengi et al., 2013), thus reducing species diversity and richness. A study by Mudzengi et al. (2013) observed significant differences between invaded and uninvaded sites in abundance, density, and richness of woody species.

Environmental variables such as soil and topography influence the occurrence of plant species and as such govern

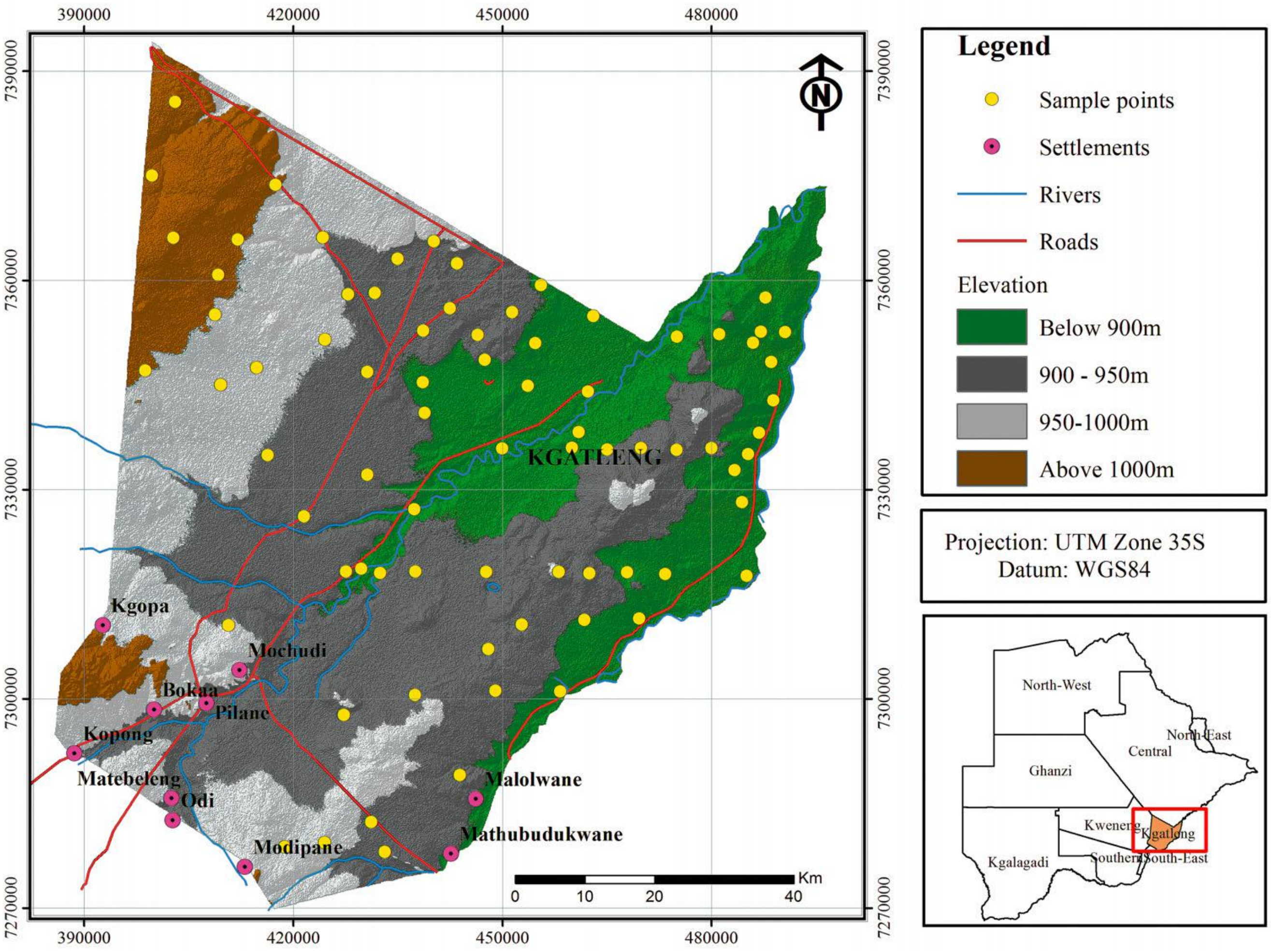

Figure 1: Location map for Kgatleng District, Botswana. Map on the bottom right shows the location of Kgatleng District in Botswana.

species composition and the diversity of the vegetation (Miyamoto et al., 2003). A study by Dahlberg (2000) in north-eastern Botswana observed that woody species richness was higher on red soil than on white soil, but species richness did not differ between ranching and communal grazing land. The study also found significantly ($P < 0.01$) more shrubs on communal land than on ranch land, probably because of less competition with the herbaceous plants, resulting in shrub seedling establishment. In Dahlberg's (2000) study conducted in the north-east district of Botswana, *Senegalia nigrescens*, *Combretum apiculatum,* and *Grewia* spp. were observed to prefer red soil whereas *Colophospermum mopane* preferred white soil. Other environmental variables such as elevation have also been noted to affect species and community diversity of vascular plants (Khan et al., 2011).

Kgatleng District, with a land area of 7960 km^2, is relatively small and is under immense pressure from different land uses. Like most communal parts of Botswana, the district is exposed to both arable farming and open-access communal livestock grazing. For sustainable management of vegetation resources, documentation of plant communities and species richness in these areas is of pivotal importance. Meanwhile, literature is lacking as far as plant diversity and richness in these areas are concerned. Thus, defining plant communities in these systems in an era of climate-change effects on vegetation is critical to serve as reference points for vegetation changes. Therefore, the objectives of the study were to (1) determine the abundance of woody (trees and shrubs) species, (2) to identify tree communities and their ecological drivers, (3) to produce a vegetation map based on Landsat imagery and the results of the phytosociological classification, and (4) to determine the species richness of the tree communities.

Methods

Study area

The study was conducted between November 2013 and December 2016. The study area covered the Kgatleng District of Botswana, located between latitude 23.88°S–24.51°S and longitude 25.89°E–26.82°E (Fig. 1). The district covers an area of 7,960 km^2 and is characterized by vegetation dominated by *Vachellia* spp., *Senegalia* spp., and *Grewia* spp., among others. Annual rainfall for the district ranges between 450 mm and 550 mm. The temperatures range between 6°C and 20°C in winter and 22°C and 30°C in summer (Bhalotra, 1987). Soils are predominantly arenosols and luvisols (Moganane,

Table 1. Abundance (individuals/ha) and indicator species for the woody plant communities identifed in Kgatleng District, Botswana.

Family	Species	Abundance ± SE (individuals/ha)	Indicator Value (IV)	Mean ± SD	p *
Unit 1 *Terminalia sericea–Maytenus tenuispina* community					
Combretaceae	*Terminalia sericea*	96.1 ± 28.14	70.2	17.1 ± 4.25	0.0002
Celastraceae	*Maytenus tenuispina*	34.6 ± 20.01	20.2	11.7 ± 5.26	0.0732
Caesalpiniaceae	*Bauhinia petersiana*	20.0 ± 8.01	18.6	9.3 ± 4.73	0.0506
Celastraceae	*Maytenussenegalensis*	12.8 ± 7.44	7.4	10.6 ± 5.12	0.7051
Unit 2 *Dichrostachys cinerea–Combretum apiculatum* community					
Mimosaceae	*Dichrostachys cinerea*	147.4 ± 22.95	57.1	23.1 ± 3.94	0.0002
Combretaceae	*Combretum apiculatum*	35.5 ± 8.11	54.3	14.7 ± 4.66	0.0002
Tiliaceae	*Grewia bicolor*	33.8 ± 6.96	51.9	18.5 ± 5.52	0.0006
Mimosaceae	*Senegalia nigrescens*	2.0 ± 1.03	28	9.3 ± 5.01	0.0056
Anacardiaceae	*Sclerocary abirrea*	0.7 ± 0.35	20	7.6 ± 4.31	0.0204
Capparaceae	*Bosciafoetida*	0.3 ± 0.22	12	6.7 ± 4.02	0.166
Euphorbiaceae	*Croton gratissimus*	8.5 ± 6.10	6.9	8.9 ± 4.66	0.6159
Combretaceae	*Combretumimberbe*	0.2 ± 0.25	4	6.5 ± 1.81	1
Euphorbiaceae	*Spirostachysafricana*	0.2 ± 0.25	4	6.5 ± 1.80	1
Rubiaceae	*Vangueriainfausta*	0.1 ± 0.12	4	6.5 ± 1.80	1
Olacaceae	*Ximeniaamericana*	0.5 ± 0.51	4	6.5 ± 1.81	1
Unit 3 *Combretum zeyheri–Vachellia tortilis* community					
Combretaceae	*Combretum zeyheri*	5.3 ± 2.64	29.4	8.8 ± 4.74	0.0028
Mimosaceae	*Vachellia tortilis*	40.6 ± 12.25	29	18.1 ± 5.33	0.0418
Tiliaceae	*Grewia retinervis*	28.9 ± 6.39	28.5	17.4 ± 5.63	0.0506
Anacardiaceae	*Rhus tenuinervis*	2.8 ± 1.09	19.5	10.3 ± 5.05	0.0532
Caesalpiniaceae	*Peltophorum africanum*	1.9 ± 0.76	17.7	9.9 ± 4.98	0.0742
Ochnaceae	*Ochna pulchra*	20.7 ± 11.40	12.4	12.9 ± 6.19	0.4311
Ebenaceae	*Diospyros lycioides*	16.2 ± 10.42	10.8	8.0 ± 4.36	0.2478
Caesalpiniaceae	*Burkea africana*	0.2 ± 0.25	8.3	6.5 ± 1.81	0.3149
Mimosaceae	*Vachellia erioloba*	3.1 ± 1.75	8.1	8.7 ± 4.53	0.4345
Mimosaceae	*Vachellia karroo*	6.4 ± 6.23	5.8	6.5 ± 3.44	0.4219
Unit 4 *Senegalia erubescens–Senegalia mellifera* community					
Mimosaceae	*Senegalia erubescens*	36.1 ± 9.42	55	17.9 ± 5.02	0.0002
Mimosaceae	*Senegalia mellifera*	31.4 ± 12.17	37.1	13.1 ± 4.74	0.0014
Capparaceae	*Boscia albitrunca*	10.1 ± 2.01	18.5	17.1 ± 4.69	0.3117
Combretaceae	*Combretum hereroense*	2.2 ± 0.83	12.4	10.2 ± 4.80	0.247
Ebenaceae	*Euclea undulata*	18.9 ± 5.78	10.8	13.9 ± 5.41	0.6847
Rhamnaceae	*Ziziphus mucronata*	2.4 ± 1.15	8.1	9.0 ± 4.49	0.4609
Mimosaceae	*Vachellia nilotica*	0.3 ± 0.28	6.9	7.4 ± 3.25	0.5999
Unit 5 *Grewia flava–Rhigozum brevispinosum* community					
Tiliaceae	*Grewia flava*	103.7 ± 14.54	56.2	23.0 ± 3.92	0.0002
Bignoniaceae	*Rhigozum brevispinosum*	24.8 ± 8.87	33.5	14.2 ± 5.72	0.01
Burseraceae	*Commiphora africana*	43.2 ± 8.86	33.3	21.9 ± 5.92	0.0486
Tiliaceae	*Grewia flavescens*	7.6 ± 3.09	24.5	12.9 ± 5.87	0.0504
Mimosaceae	*Senegalia fleckii*	8.1 ± 3.96	16.5	10.3 ± 5.20	0.1252
Celastraceae	*Maytenus buxifolia*	1.5 ± 1.15	6.5	6.6 ± 3.38	0.4657
Olacaceae	*Ximenia caffra*	0.2 ± 0.18	4.7	6.2 ± 3.26	0.6863

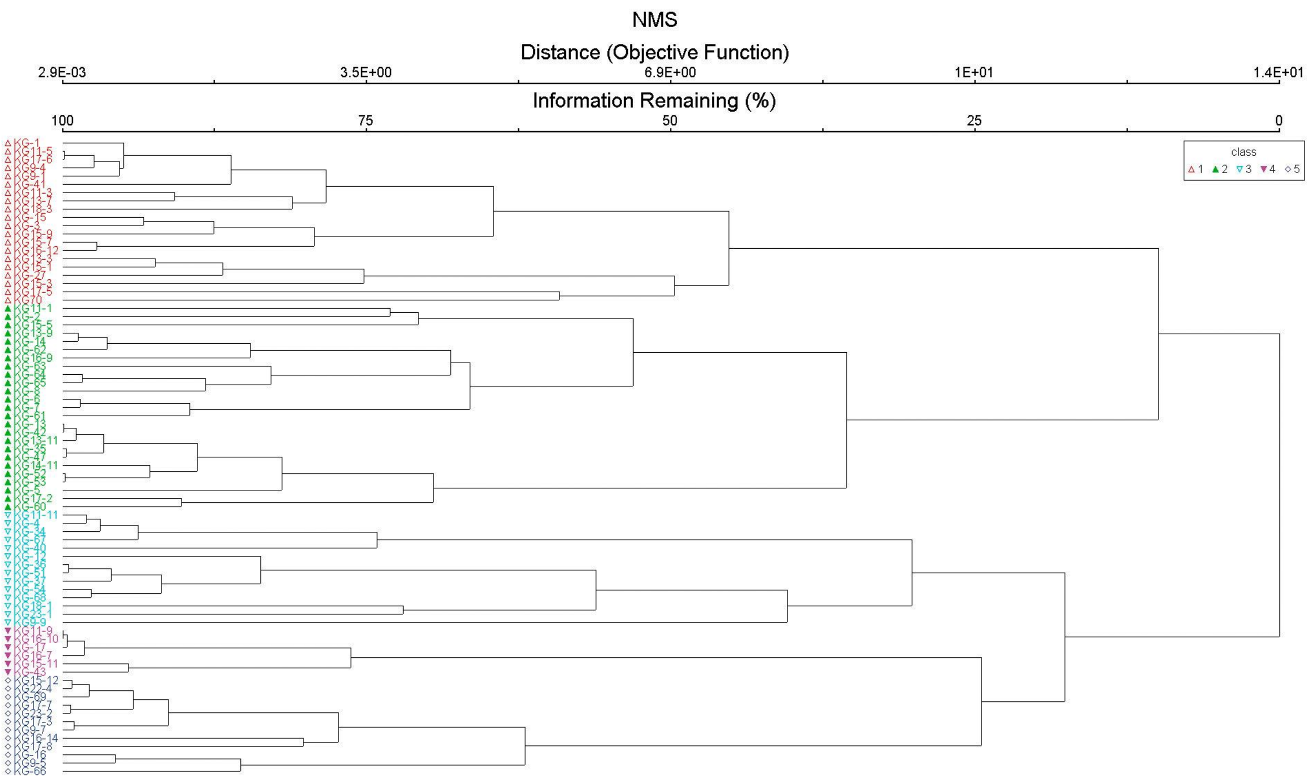

Figure 2: Cluster analysis showing the five plant communities identified in Kgatleng District, Botswana. *Terminalia sericea–Maytenus tenuispina* (1), *Dichrostachys cinerea–Combretum apiculatum* (2), *Combretum zeyheri–Vachellia tortilis* (3), *Senegalia erubescens–Senegalia mellifera* (4) and *Grewia flava–Rhigozium brevispinosum* (5).

1990). The eastern part of the district falls in the hardveld whereas the north-western part falls partly in the sandveld ecological zone (Nsinamwa et al., 2005).

Vegetation and soil sampling

Vegetation sampling involved the use of transects cutting across different vegetation types using a geographical positioning system (GPS) receiver. Before field work, satellite imagery from Google Earth was used to identify different vegetation types by contrasting colours along systematically placed transects running in a south-north direction through the entire length of the district. At each sampling point a survey pin was thrown over the shoulder, and where it landed it formed the centre point of a vegetation plot. Sampling points were established along transects at distances ranging from 5 km to 10 km apart depending on the differences in the vegetation and land use (e.g., fenced fields). The homogeneity or heterogeneity of the vegetation determined the spacing of the transects, and distances between transects were increased when the vegetation was homogenous. At each sampling point along the transects, a 50 m × 20 m quadrat, the standard plot size agreed upon for SASSCAL vegetation monitoring and mapping activities, was established. In each vegetation plot, all woody (tree and shrub) species rooted in the rectangle were counted and recorded by species. Furthermore, the percent cover of each species was estimated visually as described in Bonham (1989). A total of 77 plots were sampled (Fig. 1). Abundance data for woody species was then expressed as individuals/ha. Nomenclature for scientific names follows van Wyk & van Wyk (1997) and Kyalangalilwa et al. (2013). At each sampling plot, soil samples were also collected at a depth of 10–15 cm in the middle of each plot. Soil samples were then analysed for particle size, soil pH, and electrical conductivity (EC) following standard laboratory procedures.

Data analysis

Vegetation classification and statistical analyses

Cover data (%) of species for all 77 vegetation plots were standardised using relativisation by maximum. The data were then subjected to hierarchical cluster analysis (β linkage, β = –0.25, Sorensen distance) (McCune et al., 2002) based on 39 species distributed in the 77 plots. Indicator species analysis (Dufrene & Legendre, 1997) was used to define meaningful vegetation communities. Indicator values (IVS) were assessed for statistical significance using the Monte Carlo technique. Sorensen distance measure was used to examine differences between vegetation communities using a multi-response permutation procedure (McCune et al., 2002). Vegetation communities were plotted in ordination space using non-metric multidimensional scaling (NMDS). And the environmental variables (sand particles [%], clay particles [%], silt [%], pH, EC, inclination, and exposition) were fitted post hoc. All of these statistical analyses were performed in PCORD 6 (McCune et al., 2002).

Species richness was calculated as the mean number of species occurring in the plots of each community. To test whether species richness differs among communities, the data were analysed with one-way analysis of variance using SPSS 16.0.

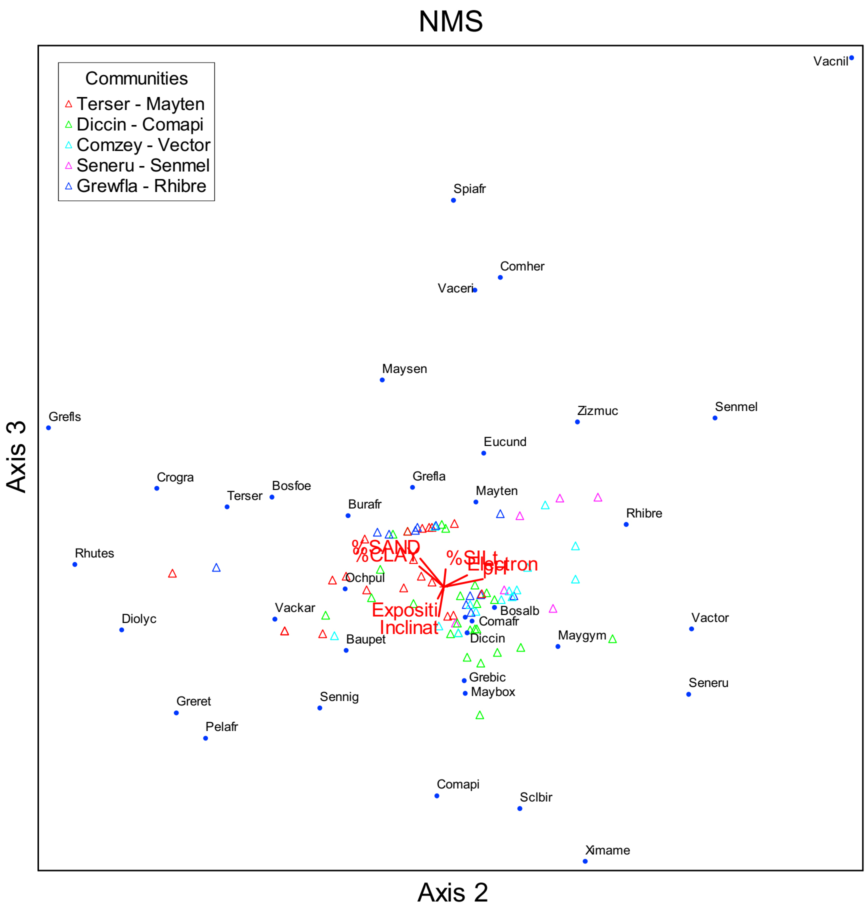

Figure 3: Non-metric multidimensional scaling (NMDS) of the vegetation data, showing the species (abbreviations show the first three letters of the genus and the epithet), the plots coloured according to the five identified communities and the environmental variables. Bauhinia petersiana – Bahpet; Boscia albitrunca – Bosalb; Boscia foetida – Bosfoe; Burkea africana – Burafr; Combretum apiculatum – Comapi; Combretum hereroense – Comher; Combretum imberbe – Comimb; Combretum zeyheri –Comzey; Commiphora africana – Comafr; Croton gratissimus – Crograt; Dichrostachys cinerea – Diccin; Diospyros lycioides –Diolyc; Euclea undulata – Eucund; Grewia bicolor –Grebic; Grewia flava – Grefla; Grewia flavescens – Grefla; Grewia retinervis – Greret; Maytenus buxifolia – Maybux; Maytenus senegalensis – Maysen; Maytenus tenuispina – Mayten; Ochna pulchra – Ochpul; Peltophorum africanum – Pelafr; Rhigozum brevispinosum – Rhibre; Rhus tenuinervis – Rhuten; Sclerocarya birrea – Sclbir; Senegalia erubescens – Seneru; Senegalia fleckii – Senfle; Senegalia mellifera – Senmil; Senegalia nigrescens – Sennig; Spirostachys Africana – Spiafr; Terminalia sericea – Terser; Vachellia erioloba – Vaceri; Vachellia karroo – Vackar; Vachellia nilotica – Vacnil; Vachellia tortilis – Vactor; Vangueria infausta – Vaninf; Ximenia Americana – Ximame; Ximenia caffra – Ximcaf; Ziziphus mucronata – Zizmuc; T*erser-Mayten: Terminalia sericea–Maytenus tenuispina, Diccin-Comapi: Dichrostachys cinerea-Combretum apiculatum, Comzey-Vactor: Combretum zeyheri-Vachellia tortilis, Seneru-Senmel: Senegalia erubescens-Senegalia mellifera and Grefla-Rhibre: Grewia flava-Rhigozium brevispinosum*.

Means were considered significantly different at $P < 0.05$. Species richness was reported as number of species per 1000 m^2. Box plots of species richness were generated from the data using SPSS 16.0.

Vegetation mapping

A vegetation map was developed to show the spatial distribution of plant communities. Four wet season scenes of Landsat 8 Operational Land Imager of 2016 were freely downloaded from USGS GloVis (Global Visualization Viewer) at a resolution of 30 m. The wet season scenes were used because during that season the vegetation is mature and the images show the vegetation in full development. However, our sampling on the ground covered both the dry and wet seasons. The scenes were atmospherically corrected using FLAASH and mosaicked using seamless mosaic in ENVI 5.1. Supervised classification was performed on the Landsat images using maximum likelihood classifier. Five vegetation communities were mapped using ENVI 5.1, and the classification results were imported into ArcMap 10.3 for finalization of the map.

Results

Diversity and abundance of woody species

A total of 15 families, 23 genera, and 39 species were observed in the district (Tab. 1). Fabaceae was the most species-rich family in the study area, and there were more species of the subfamily Mimosaceae than of the subfamily Caesalpiniaceae. The Combretaceae family had 2 genera with a total of 5 species. Only 1 species was observed for each of Bignoniaceae, Burseraceae, Ochnaceae, Rhamnaceae, and Rubiaceae families in the district.

The most abundant species in their respective communities were *Dichrostachys cinerea* with 147 individuals/ha followed by *Grewia flava* (103.7 ± 14.54 indiv./ha) and *Terminalia sericea* (96 ± 28.1 indiv./ha). Overall, abundance of the genera *Vachellia* and *Senegalia* was 50.4 and 77.6 individuals/ha, respectively (Tab. 1).

Vegetation classification and mapping

The cluster analysis identified five communities (Fig. 2). They were named based on the two species with the highest indicator values: Community 1, *Terminalia sericea–Maytenus tenuispina*; Community 2, *Dichrostachys cinerea–Combretum apiculatum*; Community 3: *Combretum zeyheri–Vachellia tortilis*; Community 4, *Senegalia erubescens–Senegalia mellifera*; and Community 5, *Grewia flava–Rhigozium brevispinosum.* The indicator species for each community are presented in Table 1. NMDS also confirmed that there were 5 distinct communities (Fig. 3). Though most of the species were clustered, the dominant indicator species for each community were clearly showing. For example, *Ximenia americana, Boscia foetida, Combretum apiculatum,* and *Dichrostachys cinerea* occurred together, characterizing the *Dichrostachys cinerea–Combretum apiculatum* community (Fig. 3). *Terminalia serecea–Maytenus tenuispina* community occurrence

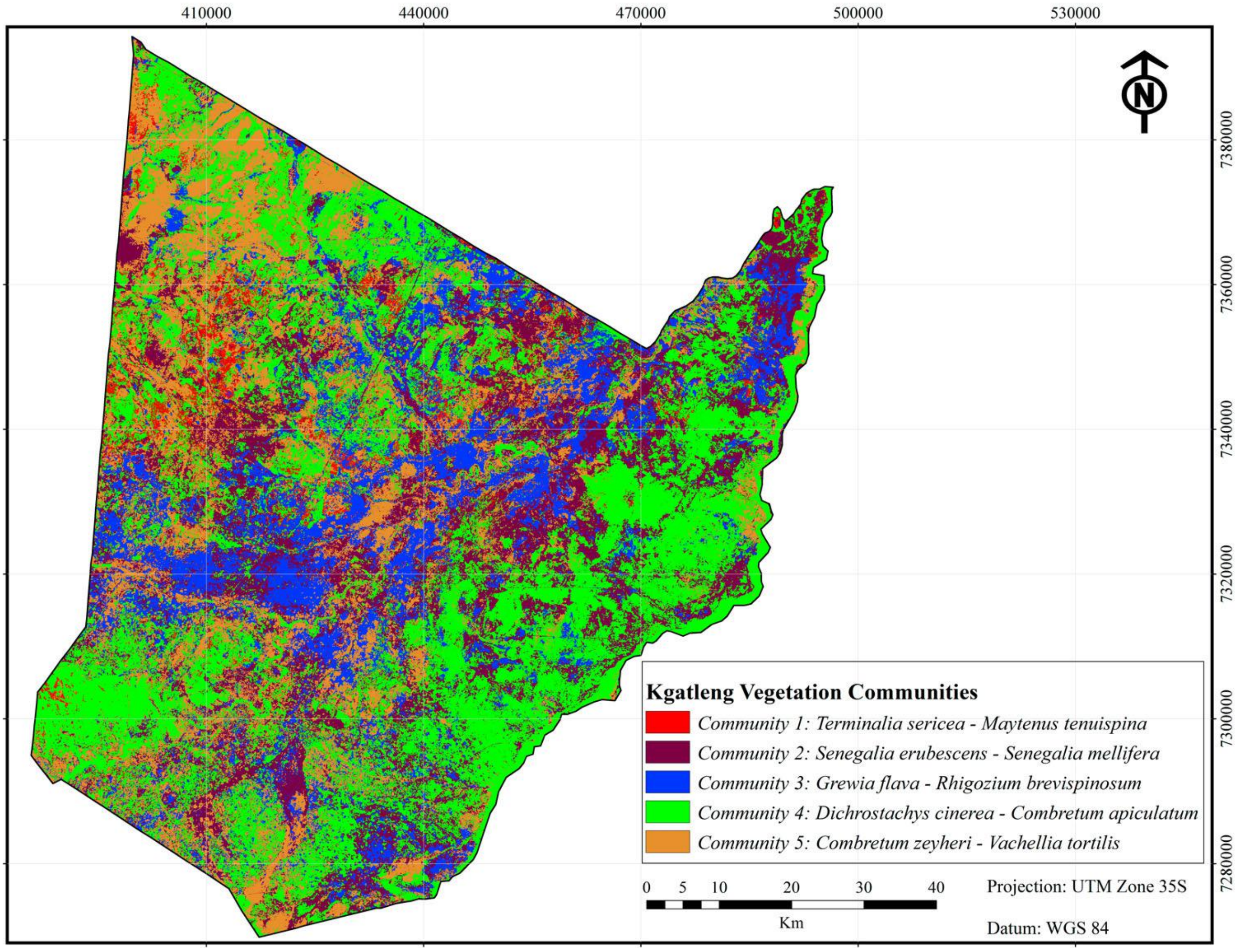

Figure 4: Vegetation map based on supervised classification of Landsat 8 scenes, showing the five communities identified in Kgatleng District, Botswana.

was influenced by the percentages of clay and sand, whereas inclination and soil pH influenced the occurrence of *Combretum zeyheri–Vachellia tortilis* communities (Fig. 3).

Upon mapping the communities, it was observed that the *Senegalia erubescens–Senegalia mellifera* community was dominant and occurred over most parts of the district, followed by the *Dichrostachys cinerea–Combretum apiculatum* community (Fig. 4). The *Terminalia sericea–Maytenus tenuispina* community covered the least area and occurred mostly towards the northern parts of the district in the sandveld.

Species richness

Species richness ranged, on average per community, between 6.4 and 7.9 species, and no significant differences were

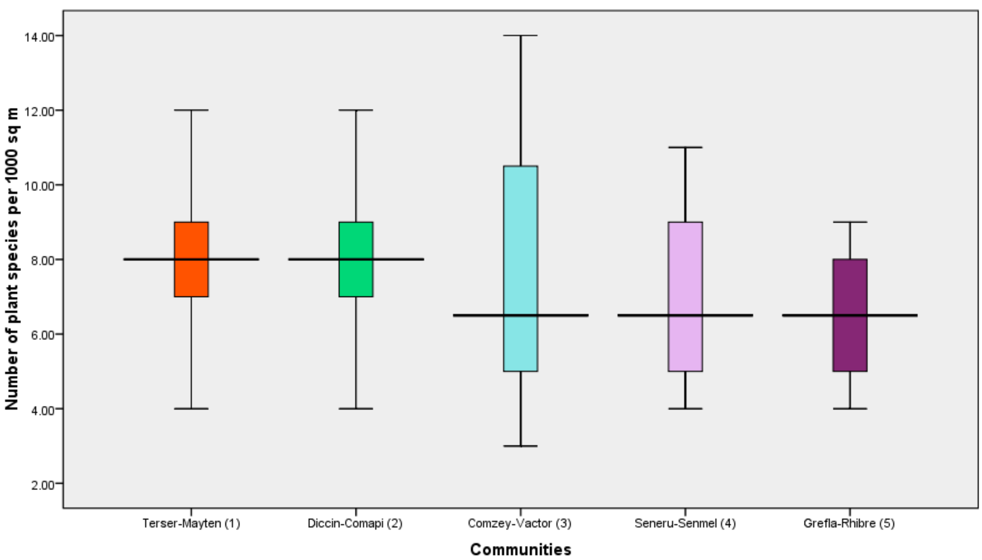

Figure 5: Box plots of the species richness of the five communities in Kgatleng District, Botswana. The abbreviations are as explained: Terser-Mayten: Terminalia sericea–Maytenus tenuispina, Diccin-Comapi: Dichrostachys cinerea-Combretum apiculatum, Comzey-Vactor: Combretum zeyheri-Vachellia tortilis, Seneru-Senmel: Senegalia erubescens-Senegalia mellifera and Grefla-Rhibre: Grewia flava-Rhigozium brevispinosum

detected among the five communities (ANOVA: $F_{4,72}$ = 1.87, P = 0.125) (Fig. 5). Interestingly, the *Senegalia erubescens–Senegalia mellifera* community that dominated the district (Fig. 4) was among the communities that had low species richness (Fig. 5), even if it was not significantly different from other communities. Species richness varied widely between plots for the *Combretum zeyheri–Vachellia tortilis* community (Fig. 5).

Densities of individuals per hectare were 1022, 748, 896, 696, and 787 for the five communities, respectively. Densities of plants did not differ significantly among communities (ANOVA: $F_{4,72}$ = 1.73, P = 0.15).

Discussion

Vegetation classification and mapping

The *Terminalia sericea–Maytenus tenuispina* community typically occurs on the sandveld north-western parts of the district, which is characterized by deep, sandy soils. Typically, *Terminalia sericea* is deep rooted and occurs on well-drained soils (van Wyk & van Wyk, 1997). According to Moore & Attwell (1999), coarse-grained soils are associated with the occurrence of tree savannas. The *Dichrostachys cinerea–Combretum apiculatum* community dominated on the eastern side of the district and occurs on the hardveld. This area is typical of bush savanna, consisting of characteristic *Dichrostachys cinerea* thickets mixed with *Grewia* species and *Combretum apiculatum* (Aganga & Omphile, 2000). In the centre of the district, the *Senegalia erubescens–Senegalia mellifera* and *Grewia flava–Rhigozium* communities were dominant. These communities comprise species such as *S. erubescens, S. mellifera*, and *G. flava*. Moleele (1998) identified these as encroaching on grazing areas in the district. Increases in these species may interfere with the predominant land use of cattle grazing as grasses are outcompeted.

Species richness

Studies have observed that plant species diversity and richness increase with an increase in plant density (Belay et al., 2013). In our study we observed high woody-plant density in the north of the district, suggesting lessened anthropogenic impact farther away from major villages in the south. However, species richness was similar across all communities. As species richness focused only on woody vegetation, it would probably have been different if all life forms were considered.

Indications of relatively high numbers of individuals from the genera *Vachellia* and *Senegalia* may be supported by earlier observations by other researchers (e.g., Moleele, 1998), who observed encroacher species such as *Senegalia mellifera* to be dominant in the north-eastern part of the district. The eastern part of the district, where bush encroachment has been identified, comprises fertile soils that support the growth of vegetation (Moganane, 1990). In the southern district of Botswana, Mosweu (2008) also observed *Vachellia* spp. encroacher species to be more in areas that were highly utilized by livestock. Because the current study covered a large area, average plant abundance was fairly low as a result of many plots sampled with variable abundances across the district, unlike Moleele's (1998) study, which was localized in a high-abundance area for the encroacher species at Oliphants Drift. Earlier studies have indicated that an area is encroached if it has ≥ 2,500 individuals/ha (e.g., Richter et al., 2001). Thus, in the current study, bush encroachment was not a concern. In contrast, in these ecosystems, *Vachellia* and *Senegalia* genera are important sources for browse and firewood. Of relevance for the local communities are also the species of the families Tiliaceae and Combretaceae, as these provide edible berries and fencing materials, respectively.

Conclusion

Woody vegetation for Kgatleng District was composed of 15 families, 23 genera, and 39 species. The five communities identified were *Terminalia sericea–Maytenus tenuispina, Dichrostachys cinerea–Combretum apiculatum, Combretum zeyheri–Vachellia tortilis, Senegalia erubescens–Senegalia mellifera,* and *Grewia flava–Rhigozium brevispinosum.* Woody species richness was not significantly different between the communities. The study provided a map of the spatial distribution of the communities in the district. The findings of this study will serve as baseline information that can be used for determining land suitability for different sectors of agriculture. The information also serves as baseline information that can be used in future to determine whether encroachment is increasing.

Acknowledgements

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References

Aganga, A.A. & Omphile, U.J. (2000) *Forage resources of Botswana.* Government Printing and Publishing Services, Gaborone, Botswana.

Belay, T.A., Totland, Ø. & Moe, S.R. (2013) Ecosystem responses to woody plant encroachment in a semiarid savanna rangeland. *Plant Ecology*, **214**, 1211.

Bhalotra, Y.P.R. (1987) *Climate of Botswana, part II: elements of climate: 1. Rainfall.* Department of Meteorological Services, Botswana.

Bonham, C.D. (1989) *Measurement for terrestrial vegetation.* John Wiley & Sons, Inc., New York, USA.

Britz, M.L. & Ward, D. (2007) Dynamics of woody vegetation in a semi-arid savanna, with a focus on bush encroachment. *African Journal of Range and Forage Science*, **24**, 131–140.

Dahlberg, A.C. (2000). Vegetation diversity and change in relation to land use, soil and rainfall — a case study from north-east district, Botswana. *Journal of Arid Environments,* **44,** 19–40.

Dufrene, M. & Legendre, P. (1997) Species assemblages and indicator species: the need for a flexible asymmetrical approach. *Ecological Monographs* **67**, 345–366.

Kgosikoma, O., Mojeremane, W. & Harvie, B.A. (2012) Pastoralists' perception and ecological knowledge on savanna ecosystem dynamics in semi-arid Botswana. *Ecology and Society*, **17**, 27.

Khan, S.M., Harper, D., Page, S. & Ahmad, H. (2011) Species and community diversity of vascular flora along environmental gradient in Naran Valley: a multivariate approach through indicator species analysis. *Pakistan Journal of Botany*, **43,** 2337–2346.

Kyalangalilwa, B., Boatwright, J.S., Daru, B.H., Maurin, O. & Van Der Bank, M. (2013) Phylogenetic position and revised classification of *Acacia s.l.* (Fabaceae: Mimosoideae) in Africa, including new combinations in *Vachellia* and *Senegalia. Botanical Journal of the Linnean Society*, **172**, 500–523.

McCune, B., Grace, J.B. & Urban, D.L. (2002) *Analysis of ecological communities.* MjM Software Design, Gleneden Beach, OR, USA.

Miyamoto, K., Suzuki, E., Kohyama, T., Seino, T., Miramanto, E. & Simbolon, H. (2003) Habitat differentiation among tree species with small-scale variation of humus depth and topography in a tropical heath forest of Central Kaliman, Indonesia. *Journal of Tropical Ecology*, **19,** 43–54.

Moganane, B.G. (1990) Soils and land suitability of Gaborone area. FAO/UNDP/Govternment of Botswana. BOT/85/011. Field Document.

Moleele, N.M. (1998) Encroacher woody plant browse as feed for cattle: cattle diet composition for three seasons at Olifants Drift, southeast Botswana. *Journal of Arid Environments,* **40**, 255–268.

Moore, A.E. & Attwell, C.A.M. (1999) Geological controls on the distribution of woody vegetation in the central Kalahari, Botswana. *South African Journal of Geology*, **102**, 350–362.

Mosweu, S. (2008) Soil resources distribution, woody plant properties and land use in a lunette dune-pan system in Kalahari, Botswana. *Scientific Research and Essay*, **3**, 442–456.

Mudzengi, C.P., Kativu, S., Murungweni, C., Dahwa., Poshiwa, X. & Shoko, M.D. (2013) Woody species composition and structure in a semi-arid environment invaded by *Dichrostachys cinerea* (l.) Wight and Arn (Fabaceae). *International Journal of Scientific and Research Publications*, **3,** 1–10.

Nsinamwa, M., Moleele, N.M. & Sebego, R.J. (2005) Vegetation patterns and nutrients in relation to grazing pressure and soils in the sandveld and hardveld communal grazing areas of Botswana. *African Journal of Range and Forage Science*, **22,** 17–28.

O'Connor, T.G.O., Puttick, J.R. & Hoffman, W.T. (2014) Bush encroachment in southern Africa: changes and causes. *African Journal of Range and Forage Science,* **31,** 67–88.

Richter, C.G.F., Snyman, H.A. & Smith, G.N. (2001) The influence of tree density on the grass layer of three semi-arid savanna types of southern Africa. *African Journal of Range and Forage Science*, **18**, 103–109.

Skarpe, C. (1990) Structure of the woody vegetation in disturbed and undisturbed arid savanna, Botswana. *Vegetatio*, **87**, 11–18.

Trollope, W.S.W. (1980) Controlling bush encroachment with fire in the savanna areas of South Africa. *Proceedings of the Annual Congresses of the Grassland Society of Southern Africa*, **15,** 173–177.

Van Wyk, B. & van Wyk, P. (1997) *Field guide to trees of southern Africa, 1st ed*. Struik Publishers, South Africa.

Ward, D. (2005) Do we understand the causes of bush encroachment in African savannas? *African Journal of Range and Forage Science*, **22**, 101–105.

References [CrossRef]

Aganga, A.A. & Omphile, U.J. (2000) *Forage resources of Botswana.* Government Printing and Publishing Services, Gaborone, Botswana.

Belay, T.A., Totland, Ø. & Moe, S.R. (2013) Ecosystem responses to woody plant encroachment in a semiarid savanna rangeland. *Plant Ecology*, **214**, 1211. CrossRef

Bhalotra, Y.P.R. (1987) *Climate of Botswana, part II: elements of climate: 1. Rainfall.* Department of Meteorological Services, Botswana.

Bonham, C.D. (1989) *Measurement for terrestrial vegetation.* John Wiley & Sons, Inc., New York, USA.

Britz, M.L. & Ward, D. (2007) Dynamics of woody vegetation in a semi-arid savanna, with a focus on bush encroachment. *African Journal of Range and Forage Science*, **24**, 131–140. CrossRef

Dahlberg, A.C. (2000). Vegetation diversity and change in relation to land use, soil and rainfall — a case study from north-east district, Botswana. *Journal of Arid Environments*, **44,** 19–40. CrossRef

Dufrene, M. & Legendre, P. (1997) Species assemblages and indicator species: the need for a flexible asymmetrical approach. *Ecological Monographs* **67**, 345–366. CrossRef

Kgosikoma, O., Mojeremane, W. & Harvie, B.A. (2012) Pastoralists' perception and ecological knowledge on savanna ecosystem dynamics in semi-arid Botswana. *Ecology and Society*, **17**, 27. CrossRef

Khan, S.M., Harper, D., Page, S. & Ahmad, H. (2011) Species and community diversity of vascular flora along environmental gradient in Naran Valley: a multivariate approach through indicator species analysis. *Pakistan Journal of Botany*, **43,** 2337–2346.

Kyalangalilwa, B., Boatwright, J.S., Daru, B.H., Maurin, O. & Van Der Bank, M. (2013) Phylogenetic position and revised classification of *Acacia s.l.* (Fabaceae: Mimosoideae) in Africa, including new combinations in *Vachellia* and *Senegalia. Botanical Journal of the Linnean Society*, **172**, 500–523. CrossRef

McCune, B., Grace, J.B. & Urban, D.L. (2002) *Analysis of ecological communities.* MjM Software Design, Gleneden Beach, OR, USA.

Miyamoto, K., Suzuki, E., Kohyama, T., Seino, T., Miramanto, E. & Simbolon, H. (2003) Habitat differentiation among tree species with small-scale variation of humus depth and topography in a tropical heath forest of Central Kaliman, Indonesia. *Journal of Tropical Ecology*, **19,** 43–54. CrossRef

Moganane, B.G. (1990) Soils and land suitability of Gaborone area. FAO/UNDP/Govternment of Botswana. BOT/85/011. Field Document.

Moleele, N.M. (1998) Encroacher woody plant browse as feed for cattle: cattle diet composition for three seasons at Olifants Drift, south-east Botswana. *Journal of Arid Environments*, **40**, 255–268. CrossRef

Moore, A.E. & Attwell, C.A.M. (1999) Geological controls on the distribution of woody vegetation in the central Kalahari, Botswana. *South African Journal of Geology*, **102**, 350–362.

Mosweu, S. (2008) Soil resources distribution, woody plant properties and land use in a lunette dune-pan system in Kalahari, Botswana. *Scientific Research and Essay*, **3**, 442–456.

Mudzengi, C.P., Kativu, S., Murungweni, C., Dahwa., Poshiwa, X. & Shoko, M.D. (2013) Woody species composition and structure in a semi-arid environment invaded by *Dichrostachys cinerea* (l.) Wight and Arn (Fabaceae). *International Journal of Scientific and Research Publications*, **3,** 1–10.

Nsinamwa, M., Moleele, N.M. & Sebego, R.J. (2005) Vegetation patterns and nutrients in relation to grazing pressure and soils in the sandveld and hardveld communal grazing areas of Botswana. *African Journal of Range and Forage Science*, **22,** 17–28. CrossRef

O'Connor, T.G.O., Puttick, J.R. & Hoffman, W.T. (2014) Bush encroachment in southern Africa: changes and causes. *African Journal of Range and Forage Science,* **31,** 67–88. CrossRef

Richter, C.G.F., Snyman, H.A. & Smith, G.N. (2001) The influence of tree density on the grass layer of three semi-arid savanna types of southern Africa. *African Journal of Range and Forage Science*, **18**, 103–109. CrossRef

Skarpe, C. (1990) Structure of the woody vegetation in disturbed and undisturbed arid savanna, Botswana. *Vegetatio*, **87**, 11–18. CrossRef

Trollope, W.S.W. (1980) Controlling bush encroachment with fire in the savanna areas of South Africa. *Proceedings of the Annual Congresses of the Grassland Society of Southern Africa*, **15,** 173–177. CrossRef

Van Wyk, B. & van Wyk, P. (1997) *Field guide to trees of southern Africa, 1st ed*. Struik Publishers, South Africa.

Ward, D. (2005) Do we understand the causes of bush encroachment in African savannas? *African Journal of Range and Forage Science*, **22**, 101–105. CrossRef

Biodiversity

SASSCAL Photo Guide to Plants of Southern Africa

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Numerous plant species — but limited tools for identification

Southern Africa is home to a rich flora, with Germishuizen & Meyer (2003) listing 24,035 taxa. To date, the number of printed publications that can be used to identify species is still limited, and there is a need to develop new tools for identification.

This was the starting point for developing the *Photo Guide to Plants of Southern Africa*. The photo guide serves as a tool that enables experts and non-scientists to make photos of identified plants available and, in return, access the identified photographs of plants that have been submitted by other experts. Thus, the photo guide has become a well-structured online database facilitating the identification of plant species, saving manpower and time.

The photo guide enables the viewing of taxonomic groups such as genera or families. Series of photos display different aspects of plants, ranging from the entire plant to details of leaves or flowers as well as information about habitat.

At the moment, 18,439 photographs of 2,589 species are represented in the photo guide.

Currently, Namibia and the western parts of South Africa are best covered, and a growing number of photographs of the other SASSCAL countries Angola, Botswana, and Zambia are being added gradually.

Free online access

The website http://www.southernafricanplants.net offers basic information regarding the current content (how many photographs, how many species) and a dialog box that allows researchers to find species by inserting only a few characters of a plant's name. For example, if pictures of *Gorteria diffusa* are wanted, it is sufficient to type 'gor dif'. The search displays first three overview images of this species and presents additional taxonomic information (family, full species name with author), along with an indication of whether more photographs are available in the database. With only one click, a species-specific overview provides further information. All photographs in the photo guide's overviews are of low resolution and show only thumbnails, but another click on a thumbnail leads to a higher-resolution version of the selected photo so that the user can see each detail of the plant in question.

Access via external applications and offline version PhotoGuide ToGo

It is possible to access species in the photo guide directly by extending the URL by genus and epithet of the species in question:
http://www.southernafricanplants.net/plantdata_main.php?extern_crit=Genus.Epithet
For example, if you are interested in *Gorteria diffusa,* the following URL is used:
http://www.southernafricanplants.net/plantdata_main.php?extern_crit= Gorteria.diffusa
The software for managing vegetation monitoring data, BIOTABase (Muche et al., 2018), uses this functionality to display photos of the species stored in its database. For field work or work in regions with bad Internet coverage, we developed the PhotoGuide ToGo. The PhotoGuide ToGo has the same functionality as the online version but must be updated manually if the online version changes.

Call for participation

Any botany expert can participate in completing the collection and filling in gaps. Photos, either individually or in a batch, can be sent to the webmaster. The photos should be accompanied by information on taxonomy, the place of observation, and the recording time as well as the name of the photographer. When the photos are inserted into the online database, the photographer can edit his or her records in an internal area of the website. We cordially invite skilled photographers, scientists, and interested institutions to contribute to the photo guide in order to make species information available to African students, scientists, and the wider public for education, planning, and conservation purposes. The photo guide is also to serve as an online discussion platform for identifying errors in plant species identifications.

References

Germishuizen, G. & Meyer, N.L. (eds.) (2003) Plants of southern Africa: an annotated checklist. *Strelitzia*, **14,** National Botanical Institute, Pretoria.

Muche, G., Schmiedel, U., Finckh, M. & Jürgens, N. (2018) BIOTABase – a unique software to handle complex biodiversity observation data and environmental data. This volume.

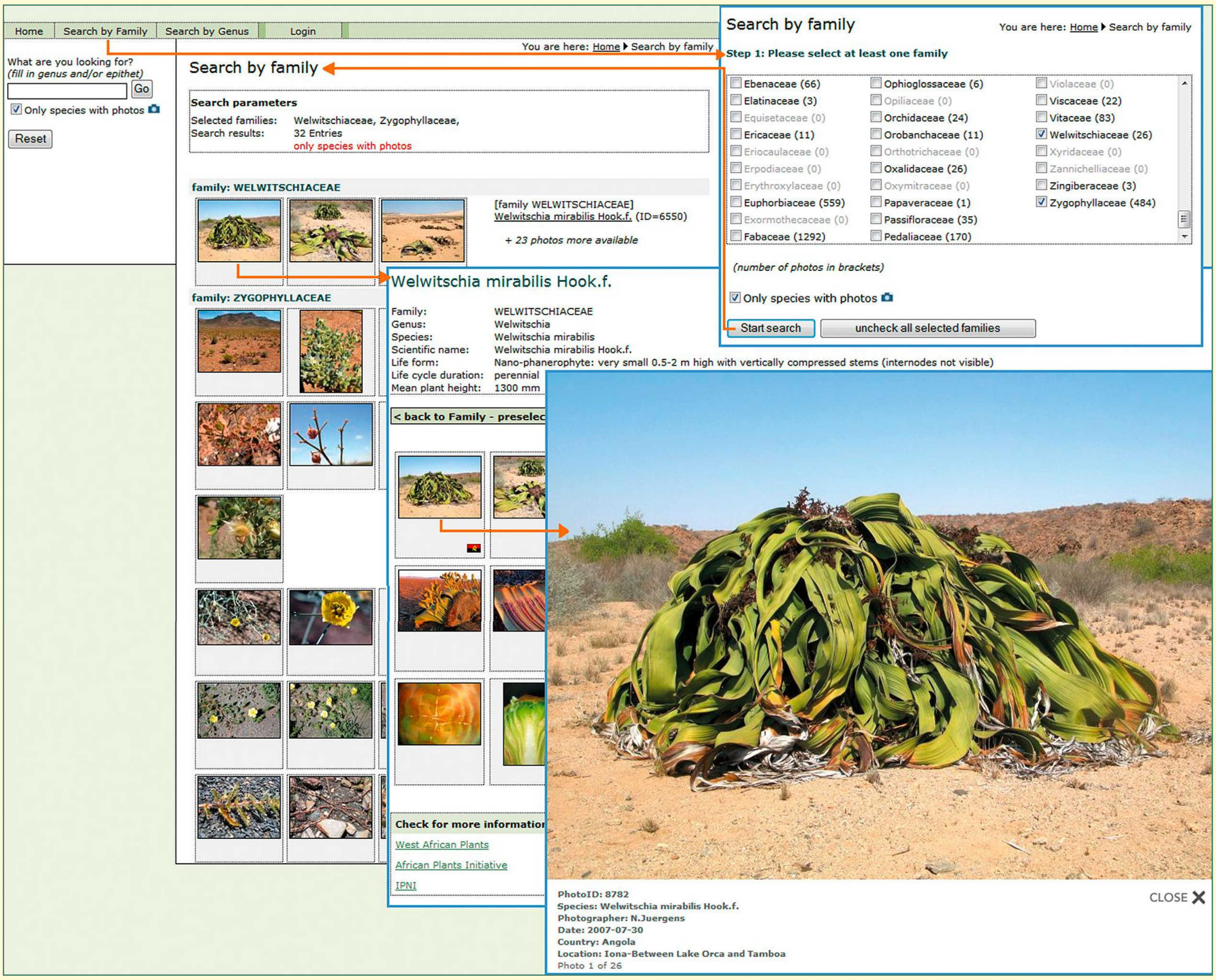

Figure 1: Search feature of the photo guide.

Figure 2: *Gorteria diffusa* Thunb. South Africa/Namaqualand/ Soebatsfontein. Photo: U. Schmiedel.

Figure 3: *Juttadinteria alba* (L. Bolus) L. Bolus. Photo: S. Rügheimer et al.

Biodiversity

Vegetation survey of the woodlands of Huíla Province

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Abstract: We conducted a vegetation survey in the woodlands of Huíla Province, Angola, with the aim of investigating woodland tree communities and species associations. Vegetation sampling was conducted using vegetation plots of 1 000 m^2 where all tree species with or above 5 cm trunk diameter (DBH) were measured. A total of 456 vegetation plots were assessed and a total of 32 080 individual trees measured. Vegetation classification using the ISOPAM algorithm resulted in 13 distinct tree communities. The most dominant family was Fabaceae, subfamily Caesalpinioideae, followed by Combretaceae and Euphorbiaceae. The classification resulted in seven tree communities belonging to the miombo woodlands, two tree communities from Mopane, two from the Baikiaea-Baphia-Terminalia woodlands, and two other distinct tree communities. In general, the miombo communities were the most diverse. The study represents the first plot-based vegetation survey for the region, and will provide the basis for the elaboration of the first vegetation map of Huíla Province.

Resumo: O levantamento da vegetação foi realizado nos bosques da Província da Huíla, Angola, com o objectivo de investigar as comunidades arbóreas e associações de espécies. O processo de amostragem da vegetação foi realizado em parcelas de 1 000 m^2, onde todas as árvores com diâmetro à altura do peito (DBH) igual ou acima de 5 cm foram medidas. Avaliámos no total 456 parcelas de vegetação, que resultou num total de 32 080 indivíduos medidos. A classificação da vegetação foi feita com recurso ao algorítimo ISOPAM que resultou em 13 comunidades distintas. A família mais dominante foi Fabaceae, subfamília Caesalpinioideae, seguida da família Combretaceae e Euphorbiaceae. A classificação da vegetação resultou em sete comunidades de miombo, duas comunidades de Mopane, duas comunidades de Baikiaea-Baphia-Terminalia, e duas outras comunidades distintas. Em geral, as comunidades de miombo foram as mais diversas. O estudo representa o primeiro levantamento feito na região com uso de parcelas, e poderá proporcionar as bases para a elaboração do primeiro mapa de vegetação da Província da Huíla.

Introduction

Angola harbours an enormous variety of habitats, with the miombo woodlands covering about 47% of the land area of the country (Huntley & Matos, 1994). Within Huíla Province, miombo is also the dominant vegetation type. Other important vegetation types include Afromontane forests and grasslands in the area of the escarpment, and *Baikiaea plurijuga* and *Colophospermum mopane* woodlands in the southwestern parts of the province. Although the region is probably one of the most botanically studied parts of the country and hosts one of the largest botanical collections in Angola at the Herbarium of Lubango (LUBA), it remained unstudied in terms of species composition and distribution of vegetation communities, as most of the previous documentation of tree species diversity conducted in the country was based commonly on floristic itineraries and not on detailed vegetation surveys (dos Santos, 1982).

Huíla Province, like many parts of Angola, faces challenges such as land degradation and deforestation, and as a result thereof, loss of biodiversity (Cabral et al., 2011). The main drivers of these processes are demand for agricultural land, fire frequency, fuelwood extraction, charcoal production, and rapid urban development (Röder et al., 2015; De Cauwer et al., 2016; Schneibel et al., 2017). There is no doubt that conservation actions are needed, aimed at preventing and mitigating ecologically harmful consequences caused by habitat modifications and land use change (Simila et al., 2006). To do so effectively first requires knowledge of the present ecosystems as well as plot-based inventories that document the floristic diversity and species composition of the woodlands.

Due to the long period of civil war experienced by Angola, information on vegetation is scarce and is generally based on early botanical work, such as the phytogeographic map of Angola (Barbosa, 1970). For the woody vegetation of Angolan miombo, only a single study is known, which resulted in the first

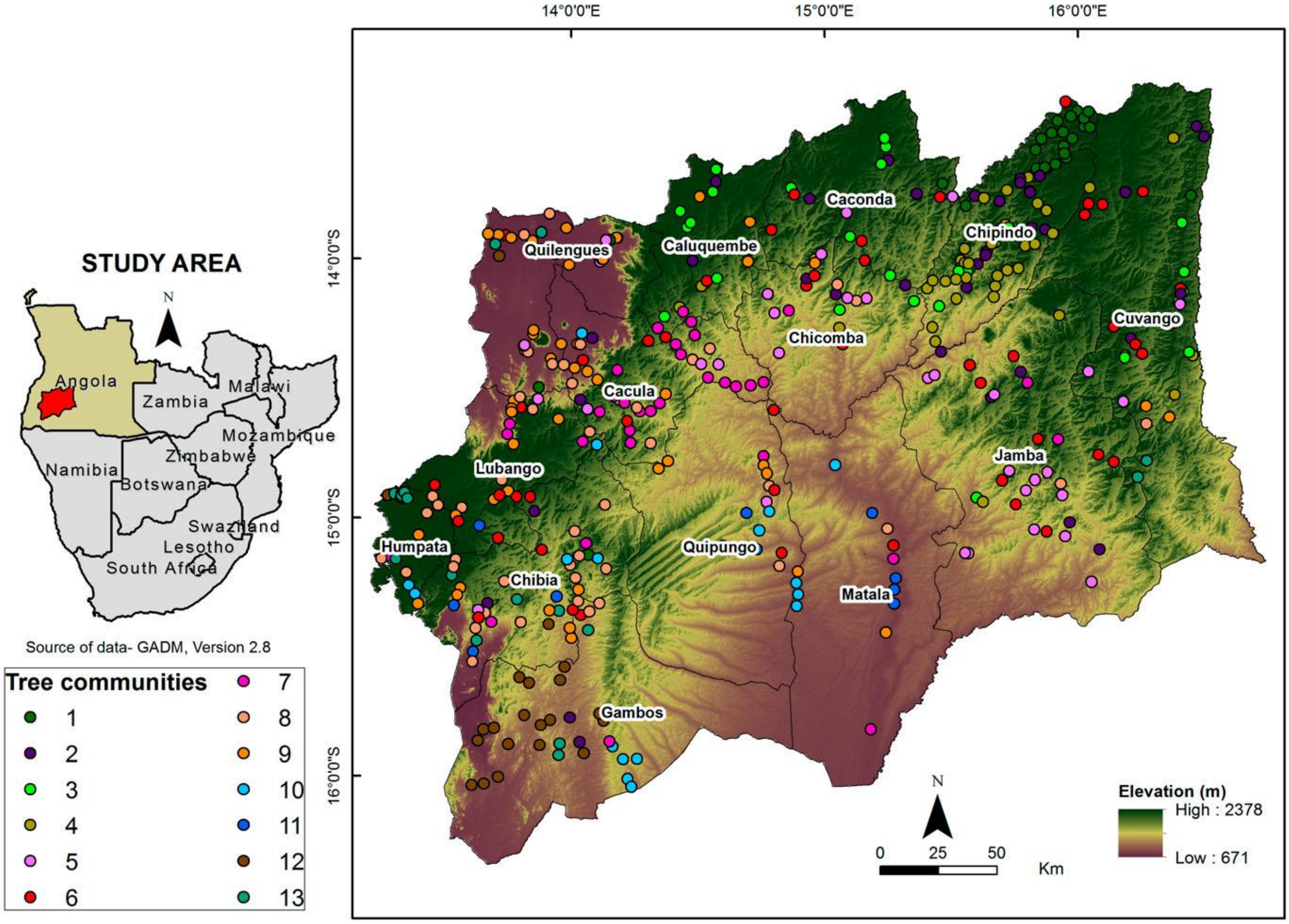

Figure 1: Map of Southern Africa with the location of the study area corresponding to Huíla Province (in red) and its administrative division into 14 municipalities. Plot locations are coloured by their corresponding woodland community types, derived from the ISOPAM algorithm.

provincial map of the Bié Province based on 144 plots (Monteiro, 1970). Recently, a few initiatives have started to document the floristic diversity of the region, though attention has been paid mostly to areas of particular botanical interest, such as the Angolan escarpment (Barker et al., 2015; Gonçalves & Goyder, 2016; Gonçalves et al., in prep.). Studies addressing floristic diversity and woody species recovery following disturbance of the miombo woodlands in south-central Angola have also been conducted (Gonçalves et al., 2017; Revermann et al., 2018). However, much remains to be done in terms of vegetation assessment to characterise the main vegetation types and species associations of Huíla Province. Thus, this study aims to provide an initial classification of the woodland plant communities of the region. This will ultimately lead to the creation of vegetation maps that are urgently needed as a tool for conservation planning and forest management.

Materials and methods

Study site

The woody vegetation was assessed in the woodlands of Huíla Province, located in southwestern Angola. The province occupies an estimated area of about 78 879 km^2, divided into 14 municipalities (Fig. 1). The climate of the region is considered tropical, with dry and cold winters and temperate rainy summers; the mean annual temperature varies from 18°C in the highlands of Humpata to 20°C in the eastern parts of the province (Köppen-Geiger, 1936). Annual precipitation increases from 700 mm in the southwest of Huíla Province to 1 000 mm in the east (Azevedo et al., 1972). According to Barbosa (1970), Huíla Province comprises at least eight vegetation types. The woodlands include the miombo, Angolan Mopane and the Zambezian *Bakiaea-Baphia* woodlands.

Vegetation sampling

We used the preliminary classification of a time-series (2001-2013) of MODIS satellite imagery and derived phenology metrics to identify major vegetation units (Stellmes et al., 2013). The map so obtained was used to create a random stratified plot sample design across the vegetation units of the study area. A total of 456 vegetation plots of 20 m x 50 m were used to assess the vegetation; within each plot, all woody species reaching a diameter at breast height (DBH) ≥ 5 cm were measured. The taxonomy of woody species followed the Angolan checklist of vascular plants (Figueiredo & Smith, 2008).

Data analysis

To understand variation in tree species and diversity within each of the derived tree communities, we calculated species richness (S) and Shannon diversity index (H'). The number of individual tree

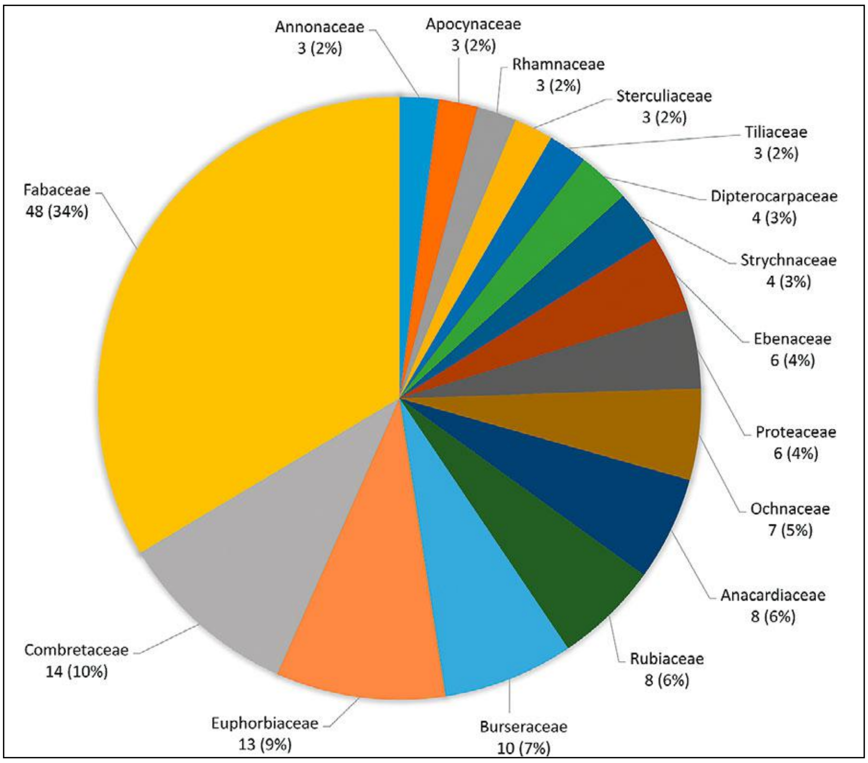

Figure 2: Number of tree species per botanical family found in Huíla Province; only families with more than two species are shown in the pie chart.

species per plot was subject to a vegetation classification using the ISOPAM algorithm in hierarchical capacity, which is based on the ordination scores from isometric feature mapping and partitioning around medoids (Schmidtlein et al., 2010). These were performed in R Version 3.2.3 (R Development Core Team, 2017) with the package ISOPAM. We selected the third hierarchical level of the dendrogram to describe tree communities and determined the diagnostic species using the phi coefficient with a threshold of 30 and a p-value of $p < 0.05$.

Results

Tree species richness

Within the 456 vegetation plots surveyed in the woodlands of Huíla Province, we recorded a total of 32 080 tree individuals corresponding to 176 tree species of 94 genera and 43 botanical families. The Fabaceae family was the most abundant in the study, reaching 34% of the total number of species. According to a recent classification, the Leguminosae/Fabaceae family comprises six subfamilies (Azani et al., 2017). Of all Fabaceae, 20% of species belonged to subfamily Caesalpinioideae, 9% to Detarioideae, and 5% to Papilionoideae, while the subfamilies Cercidoideae and Dialioideae were each represented by one species only. Other abundant families included Combretaceae (10%), Euphorbiaceae (9%), Burseraceae (7%), and other smaller families (Fig. 2).

The species accumulation curve shows that the 456 plots used in this study were sufficient to cover much of the variation observed and species diversity encountered in the studied area. At 400 plots, the graph has not yet reached its asymptotic level but is starting to converge (Fig. 3).

Vegetation classification

The vegetation classification of the ISOPAM algorithm resulted in a dendrogram in which the tree species communities can be seen. At the second hierarchical level of the dendrogram, five major floristic groups were differentiated. The dendrogram featured 13 terminal clusters corresponding to the 13 tree communities differentiated from the fourth hierarchical level (Fig. 4).

The tree species communities and species associations can be detailed as seen in Table 2. The first tree communities (**Communities 1, 2, 3, 5, 6, 7,** and **8**), with the exception of Community 4 [*Combretum collinum-Pericopsis angolensis* woodlands], constitute typical miombo woodlands with open, dense, or medium dense tree canopy, sometimes with dense understorey development (Figs. 7, 8, 9, 11, 12, 13, and 14). These communities were dominated by multiple key miombo species such as *Brachystegia boehmii*,

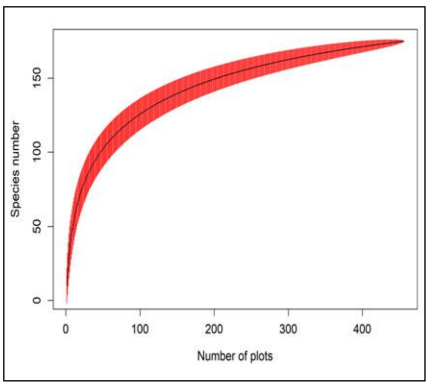

Figure 3: Species accumulation curve for trees with a diameter at breast height ≥ 5 cm measured within the sampling plots of the study area.

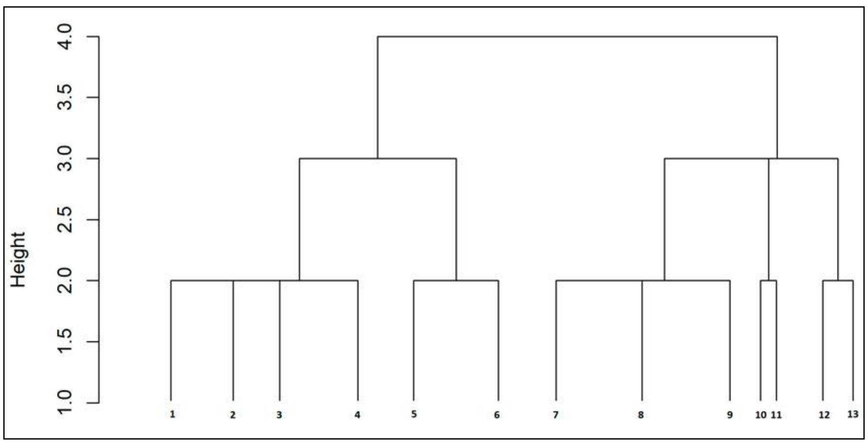

Figure 4: Community dendrogram from the ISOPAM algorithm classification with tree communities of Huíla Province; the numbered clades indicate the different tree communities.

Table 1: Overview of the tree communities of Huíla Province, their diversity values, number of indicator species, and total number of plots surveyed per tree community

Tree Communities	Cluster hierarchical level	Formation	Mean Shannon index	Mean richness	No. of indicator species	No. of plots per community
1: *Brachystegia spiciformis-Parinari curatellifolia*	1.1.1	Open woodlands	1.91	15.62	19	29
2: *Julbernardia paniculata-Brachystegia spiciformis*	1.1.2	Open woodlands	1.18	11.23	10	39
3: *Brachystegia longifolia-Diospyros kirkii*	1.1.3	Open woodlands	1.88	16.41	17	29
4: *Combretum collinum-Pericopsis angolensis*	1.1.4	Medium dense woodlands	2.07	18.29	24	49
5: *Julbernardia paniculata-Diplorhynchus condylocarpon*	1.2.1	Open dense woodlands	1.6	9.23	6	35
6: *Julbernardia paniculata-Combretum collinum*	1.2.2	Medium dense woodlands	1.43	8	3	53
7: *Brachystegia spiciformis-Pteleopsis anisoptera*	2.1.1	Open woodlands with dense understorey	1.4	6.78	3	36
8: *Julbernardia paniculata-Burkea africana*	2.1.2	Open woodlands with dense understorey	1.2	6.07	2	54
9: *Hexalobus monopetalus-Pteleopsis anisoptera*	2.1.3	Medium dense woodlands	1.74	9.53	6	55
10: *Baikiaea plurijuga-Baphia massaiensis*	2.2.1	Closed dense woodland	0.56	3	2	19
11: *Baphia massaiensis* subsp. *obovata-Terminalia sericea*	2.2.2	Medium open woodland	0.7	3.4	2	10
12: *Colophospermum mopane-Spirostachys africana*	2.3.1	Open woodlands	1.11	5.38	5	29
13: *Colophospermum mopane-Pterocarpus lucens* subsp. *antunesii*	2.3.2	Medium dense woodlands	1.79	9.53	11	19

B. floribunda, *B. longifolia* and *B. spiciformis*. The unique exception is *Julbernardia paniculata* found in four of the identified communities.

Community 4 [medium dense woodlands] This community, despite holding few key miombo species, can be considered a successional stage of miombo due to the high dominance of *Combretum* species (Fig. 10). These woodlands are normally accompanied by medium-sized tree species around 3-4 m in height, and hardwood trees of *Pericopsis angolensis*.

Community 9 [medium dense woodlands] This community occurred in lower-altitude areas covering large patches of the northwest of the region (Fig. 15). *Pteleopsis anisoptera* is the dominant tree species, and is a generally small tree. Occasionally it was found associated with other tree species such as *Cassia angolensis* and *Commiphora mollis*. In the highlands of Humpata, communities of *P. anisoptera* generally formed dense and impenetrable thickets where we also documented *Dichrostachys cinerea*, *Tarchonanthus camphoratus*, *Haplocoelum foliolosum*, *Combretum engleri,* and *Buxus benguellensis,* the latter being endemic to the region.

Community 10 [closed dense woodlands] In the study area, this community occurs in southeastern parts of the municipality of Gambos, where it forms closed dense woodlands dominated by *Combretum celastroides, C. engleri, Hippocratea parvifolia,* and sparsely trees of *Baikiaea plurijuga.* In the herbaceous layer, we documented *Adenium boehmianum*, *Gloriosa superba*, and *Hibiscus phoeniceus,* among others. These communities give way to shrublands dominated by *Baphia massaiensis* subsp. *obovata.* In reality, most of these areas are occupied by private farmers, moving towards more open woodlands in the municipality of Quipungo, where *Baikiaea plurijuga* constitutes the tallest canopy tree, occasionally associated with *Phylenoptera nelsii*, *Combretum apiculatum* subsp. *apiculatum, C. collinum*, *C. psidioides,* and *C. zeyheri*. Below the tree canopy, the vegetation is dense, being dominated again by *Baphia massaiensis* subsp. *obovata*, *Bauhinia urbaniana*, *Croton gratissimus*, *C. mubango,* and *Ochna pulchra* (Fig. 16). Communities of *Baikiaea-Baphia* also cover large parts of Bicuar National Park (BNP). Here, these woodlands formerly appeared associated with *Schinziophyton rautanenii*, though at present, we found few and sparse trees at the woodland edges of the park and also in the municipal limits of Quipungo and Chicomba.

Community 11 [medium open woodlands] Patches of *Baphia-Terminalia* were also found in the municipality of Matala, and partially along Bicuar moving south on the way to Mulondo (Fig. 17). The understorey was commonly dominated by *Mundulea sericea, Vitex mombassae, Ximenia americana* and *X. caffra*, while in the herbaceous layer we documented *Scadoxus multiflorus*, *Grewia monticola,* and *Erithrina baumii*.

Community 12 [open woodlands] This community represents woodlands dominated primarily by *Colophospermum mopane* and normally occurs at low altitudes below 1 000 m, as in the municipalities of Chibia, Gambos, and Quilengues. Here, *C. mopane* constitutes the most dominant tree species (Fig. 18), and appears occasionally associated with *Spirostachys africana*, *Acacia nilotica,* and *Pterocarpus rotundifolius*. The shrub layer is dominated by *Commiphora africana*, *Grewia welwitschii, Bolusanthus speciosus,* and *Pseudomussaenda monteiroi,* mostly in the Mopane woodlands of Quilengues. In some of drier areas of the region, we found *Commiphora mollis, Commiphora multijuga, Terminalia prunioides*, *Schrebera alata*, and *Rhigozum obovatum,* also associated with *Colophospermum mopane* woodlands.

Community 13 [medium dense woodlands]

These communities cover areas in the southwestern parts of the region around Chibia and Gambos. *Colophospermum mopane* is sparsely distributed along with *Pterocarpus lucens* spp. *Antunesii*; other tree species include *Commiphora angolensis*, *Kirkia acuminata*, *Peltophorum africanum*, *Ptaerxylon obliquum,* and *Entada abyssinica*. The generally closed understorey is dominated by thorny species such as *Acacia nilotica*, *A. ataxacantha*, *A. welwitschii*, *A. tortilis,* and *Commiphora africana* (Fig. 19).

Biodiversity

Figure 7: *Brachystegia spiciformis-Parinari curatellifolia* woodlands [open woodlands] (photo: F. Gonçalves).

Figure 8: *Julbernardia paniculata-Brachystegia spiciformis* woodlands [open woodlands] (photo: F. Gonçalves).

Figure 9: *Brachystegia spiciformis-Diospyros kirkii* woodlands [open woodlands] (photo: F. Gonçalves).

Figure 10: *Combretum collinum-Pericopsis angolensis* woodlands [medium dense woodlands with dense understorey] (photo: F. Gonçalves).

Figure 11: *Julbernardia paniculata-Diplorhynchus condylocarpon* woodlands [open dense woodlands] (photo: F. Gonçalves).

Figure 12: *Julbernardia paniculata-Combretum collinum* woodlands [medium dense woodlands] (photo: F. Gonçalves).

Figure 13: *Brachystegia spiciformis-Pteleopsis anisoptera* woodlands [open woodlands with dense understorey] (photo: F. Gonçalves).

Figure 14: *Julbernardia paniculata-Burkea africana* woodlands [open woodlands with dense understorey] (photo: F. Gonçalves).

Figure 15: *Hexalobus monopetalus-Pteleopsis anisoptera* woodlands [medium dense woodlands] (photo: F. Gonçalves).

Figure 16: *Baikiaea plurijuga-Baphia massaiaiensis* subsp. *obovata* woodlands [closed dense woodlands] (photo: F. Gonçalves).

Figure 17: *Baphia massaiensis* subsp. *obovata-Terminalia sericea* woodlands [medium open woodlands] (photo: F. Gonçalves).

Figure 18: *Colophospermum mopane-Spirostachys africana* woodlands [open woodlands] (photo: F. Gonçalves).

Figure 19: *Colophospermum mopane-Pteocarpus lucens* subsp. *antunesii* [medium dense woodlands] (photo: F. Gonçalves).

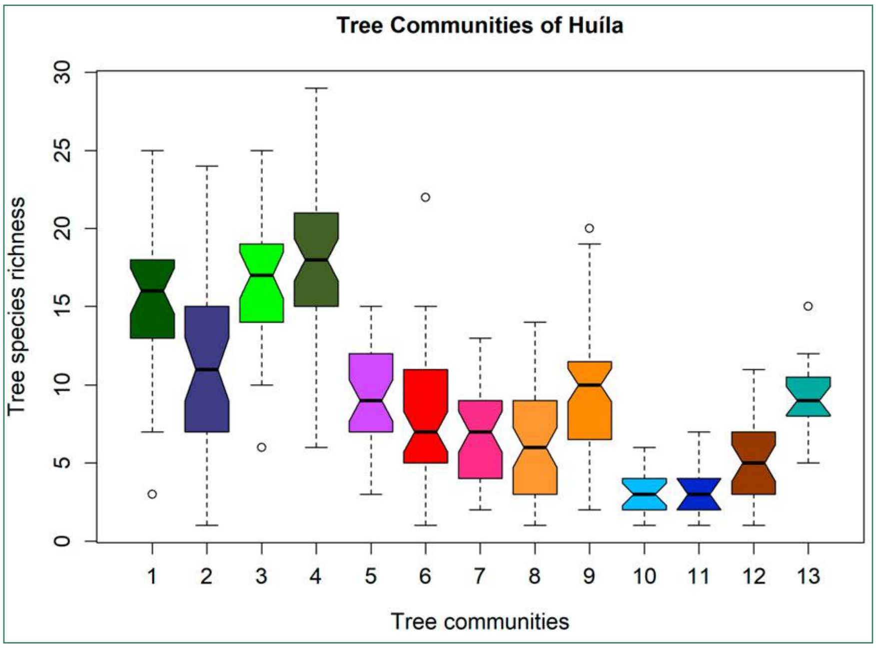

Figure 5: Box plots depicting the tree species richness in the 13 identified communities.

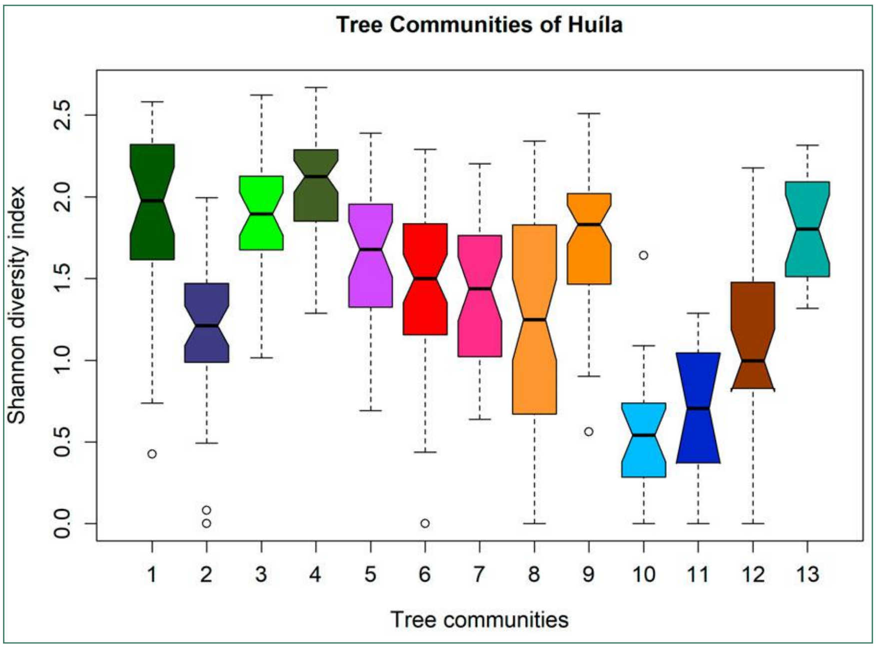

Figure 6: Shannon index of the plots of the 13 tree communities.

Tree species diversity

The inspection of diversity of the main floristic groups showed that in general, miombo woodlands with *Brachystegia spiciformis-Parinari curatellifolia*, *B. longifolia-Diospyros kirkii,* and *Julbernardia paniculata-Diplorhynchus condylocarpon* [Communities 1, 3, 5] have the highest species richness (Tab. 1), followed by *Hexalobus monopetalus-Pteleopsis anisoptera* woodlands [Community 9] and *Colophospermum mopane-Pterocarpus lucens* subsp. *antunesii* woodlands [Community 13]. The tree community with the highest tree species richness was *Combretum collinum-Pericopsis angolensis* woodlands [Community 4]. Communities of *Julbernardia paniculata-Brachystegia spiciformis* [Community 2], *Baikiaea plurijuga-Baphia massaiensis* subsp. *obovata* [Community 10], *Baphia massaiensis* ssp *obovata-Terminalia sericea* [Community 11], and *Colophospermum mopane-Pterocarpus lucens* subsp. *antunesii* [Community 12] showed the lowest species richness (Fig. 5).

The communities of the first major cluster, Communities 1-5, were the most diverse as measured by the Shannon diversity index, with the exception of Community 2. These communities also showed the highest species richness and greatest number of indicator species of communities. The second most diverse community was represented by tree communities 6 to 9 and 13 (Fig. 6). Community 9 showed also the highest number of plots sampled. The second highest number of plots sampled was found in Community 8. Despite the high sampling effort in these communities, they demonstrated very low species richness as well as low numbers of indicator species (Tab. 1)

Discussion

Diversity of the woodlands of Huíla Province

This study represents the first plot-based woody vegetation assessment of Huíla Province in Angola, aiming to characterise and describe the woodlands of the region. A total of 456 plots were surveyed in the region, sufficient to document major floristic groups occurring in the study area, as evidenced by the species accumulation curve. This pattern may imply that any further increase of sampling effort would be expected to lead to inclusion of additional rare species, as the sample size of 456 was high and may capture almost all woody species occurring in the region, and can be useful to characterise the species diversity and relationship between woody species and site conditions. As mentioned before, most of the previous studies carried out in the country date to the colonial era. These studies characterised the vegetation types based on general aspects or were limited to dominant species only (but see Revermann et al., 2018). As with other parts of Angola, there is still a great deal of work to be done to describe the vegetation of Huíla Province. Barbosa (1970) recognises about eight vegetation types for the Huíla region, including the most important woodlands surrounding the study area. With the present study, we are able to document 13 distinct tree communities within the region; most of them constitute fairly typical miombo woodlands, dominated by the Fabaceae family, of which the subfamily Caesalpinioideae is the largest. The dominance of the Fabaceae family within the miombo eco-region has been widely reported in various studies (Byers, 2001; Munishi et al., 2011). Within the study area of Huíla Province, miombo woodlands occupy large areas, being relatively dense with canopy tree species around 12-15 m in height in the municipalities of Chipindo and Cuvango. The woodlands become open with increasing altitude, as observed in Caconda, Caluquembe, and patches of the Humpata plateau, and due to high land use pressure caused by agriculture, the woodlands appear also relatively open in the municipality of Jamba.

The mean Shannon index values found in the study area were generally low, with the exception of Community 4 [*Combretum collinum-Pericopsis angolensis* woodlands] with a mean H' equal to 2.07. The highest value of Shannon diversity found in this community supports the view that these woodlands may represent regrowth of typical miombo woodlands, as areas heavily impacted by agriculture are reported to hold tree species with high light demand and fast growth, like many *Combretum* species (Jew et al., 2016). These species recruit and establish easily following disturbance and in this way additional species are added to the otherwise typical miombo species (Banda et al., 2006; Gonçalves et al., 2017). The presence of standing trees of the hardwood species *Pericopsis angolensis* was also documented in early succession of the south-central Angolan miombo woodlands (Gonçalves et al., 2017). A threshold of H' = 2 has been mentioned as the minimum value above which an ecosystem can be regarded as medium to high diversity (Giliba et al., 2011). The mean Shannon diversity index found in the Mopane woodlands of the study area was relatively low compared to similar habitats in northern Botswana; this is attributed to anthropogenic disturbance, suggesting that non-protected woodlands are negatively impacted by human activity, with a direct effect on the composition and diversity of species (Teketay et al., 2018). Within the study area we found H' values below 1; this may not only be related to the minimum number of plots surveyed, but also to the monodominance of single tree species such as *Baikiaea plurijuga-Baphia massaiensis-Terminalia sericea*. The Shannon index may be strongly influenced by the occurrence of rare species such as *Entandrophragma spicatum,* which can be found in the area associated to the woodlands. *E. spicatum* was reported to be very rare in the study area and probably in risk of local extinction due to its high value as timber (Barbosa, 1970).

Vegetation classification

The Angolan miombo woodlands cover an extensive area of central Angola, extending into Democratic Republic of Congo (Burgess et al., 2004). Most of this eco-region is found at elevations between 1 000-1 500 m above sea level and includes the highlands of Huíla, Huambo, and Bié (Barbosa, 1970; Huntley, 1974a). Within our study area, miombo woodlands covered large areas, ranging from high rainfall sites in the north, where the woodlands seem to be much denser and almost intact, towards the southeastern and western parts of the region, where the woodlands are generally sparser (Communities **1, 2, 3, 5, 6, 7,** and **8**). Miombo woodlands show variations in terms of density and species composition throughout the region, with differences in species composition being more evident at local scale. Local abiotic conditions and changes from *Brachystegia spiciformis* to *Julbernardia paniculata* communities, together with various other woody species, may also influence the stand structure and composition of the woodlands (Revermann & Finckh, 2013). Signs of tree damage caused by fire, woodcutting, and/or agriculture activity were also documented; this is a stark reminder that fire frequency, together with other human disturbance, plays a major role in miombo woodland dynamics, affecting physical structure, composition of species, and also woodland recovery following disturbance (Chidumayo, 2002; Furley et al., 2008).

Community 4, *Combretum collinum-Pericopsis angolensis* woodlands, was found associated with key miombo and non-miombo species, mainly in the municipalities of Caconda, Caluquembe, and Chicomba. Similar patterns of key miombo species occurring together with other woody species have also been documented in the Tanzanian miombo woodlands (Banda et al., 2008). These findings contrast with the pattern usually considered common for miombo woodlands, suggesting that on a larger spatial scale, the species composition of miombo is very high, and common genera as *Brachystegia*, *Julbernardia,* and *Isoberlinia* are not always dominant at the local scale (Mwakalukwa et al., 2014).

Community 9, *Hexalobus monopetalus-Pteleopsis anisoptera* woodlands, was widely distributed across the region. Stands of *Hexalobus monopetalus* are reported to occur mainly at low altitudes in southern Africa (Coates Palgrave, 2005), but in the study area, these species also appeared to be very common in disturbed woodlands. This community was also found on rocky outcrops and mountainous areas of the Quilengues and Humpata plateau. Small trees of key miombo species such as *Brachystegia spiciformis* and

Julbernardia paniculata were commonly found associated to the community (Gonçalves, 2009).

Community 10, *Baikiaea plurijuga-Baphia massaiensis* subsp. *obovata* woodlands, belongs to the Zambezian *Baikiaea* woodlands eco-region, which forms a mosaic of *Baikiaea plurijuga*-dominated forest, woodlands, thickets, and secondary grassland in Angola, Namibia, Botswana, Zambia, and Zimbabwe (Burgess et al., 2004). These dense woodlands, described in the southeastern parts of Gambos, appear similar to the dense *Baikiaea-Burkea* woodlands first described for the Okavango basin along the Cubango River, characterised by a closed canopy and thicket-like understorey (Revermann & Finckh, 2013; Wallenfang et al., 2015). Further north of Gambos, *Baphia massaiensis* subsp. *obovata* dominates the landscape; this attracts private farmers to these areas, as this species is of high nutritional value for livestock (Maiato & Sweet, 2011). The *Baikiaea* woodlands become more open and constitute one of the dominant vegetation types of Quipungo within the administrative division of Bicuar National Park (BNP). A detailed vegetation account of this area points to about six vegetation communities occurring within the BNP, including woodlands, shrublands, and grasslands with aquatic and semi-aquatic vegetation (Teixeira, 1968). We documented *Baikiaea plurijuga-Baphia massaiensis* subsp. *obovata* woodlands during the field survey as one of the major woody vegetation components in the region, which is not clearly described in this previous study. Barbosa (1970) described these woodlands as occupying large areas of the BNP. The *Baikiaea-Baphia* woodlands here can be considered part of an extensive area of dry tropical woodland in southern Africa; in Angola, it has its southeast limit in deep Kalahari sands along the Angolan-Namibian border. Here the canopy is dominated by tree species such as *Schinziophyton rautanenii*, *Guibourtia coleosperma,* and *Pterocarpus angolensis*; pure stands of *Baikiaea plurijuga* only rarely occur (Gonçalves et al., 2018). The woodlands in the BNP may represent the most intact unit of this vegetation community in Huíla Province, as the surrounding areas of Matala and Quipungo were largely depleted, most likely by timber over-exploitation and clearance of large areas for agriculture purposes in the two municipalities.

To the south, moving towards Mulondo in the municipality of Matala, we were able to characterise woodland as *Baphia massaiensis-Terminalia sericea* woodlands (Community 11). This community also covers large areas of Bicuar National Park. Shrubby species within the community were generally very few, and included *Vitex mombassae and Grewia* spp. The previous vegetation studies refer to this community as *Terminalia sericea, Acacia nilotica, A. tristis,* or *Hippocratea-Baphia-Croton-Combretum* spp. shrublands, where *Baikiaea* may or may not occur (Teixeira, 1968; Barbosa, 1970). In fact, *T. sericea* may also appear associated to these species in our study area; however, we were not able to assess these shrublands, as they generally form dense and almost impenetrable thicket, and standing trees rarely occur.

Mopane woodlands cover an estimated area of 55 000 km^2 in southern Africa (Makhado et al., 2014). The woodlands stretch between Angola and Namibia in the southwest, from the marginal mountain chain at the base of Serra da Chela to more open and sub-desert habitats (Barbosa, 1970; Menezes, 1971). The Mopane woodlands in Angola grow over vast areas, and are typically associated with ferralitic and black clay soils. Within these areas, *C. mopane* appears associated with tree species, which mirrors the much drier climate previously documented between the municipalities of Caraculo and Virei in the Namibe Province (Maiato & Sweet, 2011). In our study, two communities (Communities 12 and 13) with *C. mopane* as a character species were identified with only slightly differing species composition. Community 13, *Colophospermum mopane-Pterocarpus lucens* subsp. *antunesii* woodlands was mostly characteristic of the drier areas of Huíla Province. This community may represent a vegetation of contact between medium open miombo woodlands of *Julbernardia paniculata*, *Brachystegia spicifomis* and *B. boehmii* of Chibia and typical Mopane woodlands further south (Barbosa, 1970). Further indicator species of the community were *Commiphora* species, and shrubs of *Croton mubango,* common in the understorey.

Conclusion

Information on Angolan vegetation is scarce, as most studies conducted in the country date back to the colonial era. This study, carried out in Huíla Province, represents the first plot-based vegetation survey in this province and provides the first vegetation classification for this region. A high sampling effort guaranteed that most tree species expected to occur in the Huíla were recorded and that representative tree communities were identified. As such, this survey constitutes the basis for the first detailed vegetation map of the province. Additionally, a deeper analysis of environmental drivers of vegetation patterns will be needed in order to explain the distribution and variation of species composition and diversity in the woodlands of Huíla Province.

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References

Azani, N., Babineau, M., Bailey, C.D., et al. (2017) A new subfamily classification of the Leguminasae based on a taxonomically comprehensive phylogeny. *Taxon,* **66,**44–77.

Azevedo, A.L., Refrega, A.A.G., Sousa, E.C., et al. (1972). Caracterização Sumária das Condições Ambientais de Angola. Cursos Superiores de Agronomia e de Silvicultura, Universidade de Luanda, Nova Lisboa, Angola.

Banda, T., Schwartz, M.W. & Caro, T. (2006) Woody vegetation structure and composition along a protection gradient in a miombo ecosystem of western Tanzania. *Forest Ecology and Management*, **230**, 179–185.

Banda, T., Mwangulango, N., Meyer, B. et al. (2008) The woodland vegetation of the Katavi--Rukwa ecosystem in western Tanzania. *Forest Ecology and Managemnet*, **255**, 3382–3395.

Barbosa, L.A.G. (1970). Carta Fitogeográfica de Angola. Instituto de Investigação Científica de Angola. Oficinas Gerais de Angola, Luanda, Angola.

Barker, N., Clark, R., Maiato, F., Francisco, D., Neef, G. & Goyder D. (2015). Learning the ABCs: Angolan botanical collecting Part 2: Bush pilots and old volcanoes. *Veld & Flora*, **101**, 116–119.

Burgess, N., Hales, J.D., Underwood, E. et al. (2004) *Terrestrial ecoregions of Africa and Madagascar.* World Wildlife Fund (WWF). Island Press, Washington, DC.

Byers, A.B. (2001) *Conserving the miombo ecoregion*. Reconnaissance Summary. WWF, Southern Africa Regional Program Office, Harare, Zimbabwe.

Cabral, A.I.R., Vasconcelos, M.J., Oom, D. & Sardinha R (2011) Spatial dynamics and quantification of deforestation in the central-plateau woodlands of Angola (1990–2009). *Applied Geography*, **31**, 1185–1193.

Chidumayo, E.N. (2002) Changes in miombo woodland structure under different land tenure and use systems in central Zambia. *Journal of Biogeography*, **29**, 1619–1626.

Coates Palgrave, M. (2005) *Keith Coates Palgrave: Trees of Southern Africa*. Edn 3. Struik Publishers, Cape Town, South Africa.

De Cauwer, V., Geldenhuys, C. J., Aerts, R., Kabajani, M., & Muys, B. (2016). Patterns of forest composition and their long-term environmental drivers in the tropical dry forest transition zone of southern Africa. *Forest Ecosystems,* **3**, 23.

dos Santos, R.M. (1982) *Itinerários florísticos e carta da vegetação do Cuando Cubango*. Instituto de Investigação Científica Tropical/Junta de Investigações Científicas do Ultramar, Lisboa, Portugal.

Figueiredo, E., & Smith, G.F. (2008). *Plants of Angola/Plantas de Angola*. South African National Biodiversity Institute, Pretoria, South Africa.

Furley, P.A., Rees, R.M., Ryan, C.M. & Saiz, G. (2008) Savanna burning and the assessment of long-term fire experiments with particular reference to Zimbabwe. *Progress in Physical Geography*, **32**, 611–634

Giliba, R.A., Boon, E.K., Kayombo, C.J., Musamba, E.B., Kashindye, A.M. & Shayo, P.F. (2011) Species composition, richness and diversity in miombo woodland of Bereku Forest Reserve Tanzania. *Journal of Biodiversity*, **2**, 1–7.

Gonçalves, F.M.P. (2009) Contribuição para o conhecimento, distribuição e conservação da flora da Província da Huíla. Tese de Licenciatura.

Gonçalves, F.M.P. & Goyder, D.J. (2016). A brief botanical survey into Kumbira forest, an isolated patch of Guineo-Congolian biome. *Phytokeys*, **65**, 1–14

Gonçalves, F.M.P., Revermann, R., Gomes, A.L., Aidar, M.P.M., Finckh, M. & Juergens, N. (2017) Tree species diversity and composition of miombo woodlands in south-central Angola: A chronosequence of forest recovery after shifting cultivation. *International Journal of Forest Research,* **2017,** 1–13.

Gonçalves, F.M.P., Revermann, R., Cachissapa, M.J., Gomes, A.L., & Aidar, M.P.M. (2018) Species diversity, population structure, and regeneration of woody species in fallows and mature stands of tropical woodlands of Southeast Angola. *Journal of Forestry Research,* **2018,** 1–11.

Huntley, B. (1974a) Outlines of wildlife conservation in Angola. *Journal of the South African Wildlife Management Association*, **4**, 157–166.

Huntley, B.J. & Matos, E.M. (1994) Botanical diversity and its conservation in Angola. *Strelitzia* 1, Pretoria, South Africa.

Köppen, W. (1936). Handbuch der Climatologie, Ed. *Koppen Geiger*.

Kindt, R. & Coe R. (2005). *Tree diversity analysis: A manual and software for common statistical methods for ecological and biodiversity studies*. World Agroforestry Centre, Nairobi, Kenya.

Makhado, R.A., Mapaure, I., Potgieter, M.J., Luus-Powell, W.J. & Saidi, A.T. (2014) Factors influencing the adaptation and distribution of *Colophospermum mopane* in southern Africa's mopane savannah: A review. *Bothalia*, **44**, 1–9.

Maiato, F. & Sweet, R.J. (2011) Guia de Pasto nas Áreas de Transumância, Angola. Manuais Transumância, GFA Consulting Group, Luanda, Angola.

Menezes, A. (1971) Estudo Fito-ecológico da região do Mucope e Carta da Vegetação. Sep. do Bol. Inst. Invest. Cient. Ang., Luanda, Angola.

Munishi, K.T., Temu, R.A.P.C., Soka, G. (2011) Plant communities and tree species associations in a miombo ecosystem in the Lake Rukwa basin, southern Tanzania: Implications for conservation. *Journal of Ecology and the Natural Environment* **3**, 63–71.

Mwakalukwa, E.E., Meilby, H. and Treue, T. (2014) Floristic composition, structure, and species associations of dry miombo woodland in Tanzania. *International Journal of Forest Research*, **2014**, 1–15.

R Development Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Revermann, R. & Finckh, M. (2013) Okavango Basin: Vegetation. *Biodiversity & Ecology*, **5**, 29–35.

Revermann, R., Oldeland, J., Gonçalvess, F.M., Luther-Mosebach, J., Gomes, A.L., Juergens, N. & Finckh, M. (2018) Dry tropical forests and woodlands of the Cubango Basin in southern Africa: A first classification and assessment of their woody species diversity. *Phytocoenologia*, **48**, 23–50.

Röder, A., Pröpper, M., Stellmes, M., Schneibel, A., & Hill, J. (2016). Reprint of "Assessing urban growth and rural land use transformations in a cross-border situation in Northern Namibia and Southern Angola." Land Use Policy, 53, 97–111.

Schmidtlein, S., Tichý, L., Feilhauer, H., Faude, U. (2010) A brute-force approach to vegetation classification. *Journal of Vegetation Science,* **21**, 1162–1171.

Schneibel, A., Frantz, D., Röder, A., Stellmes, M., Fischer, K., & Hill, J. (2017) Using annual landsat time series for the detection of dry forest degradation processes in south-central Angola. *Remote Sensing,* **9**, 905.

Simila, M., Kouki, J., Mönkkönen, M., Sippola, A. & Huhta, E. (2006) Co-variation and indicators of species diversity: Can richness of forest-dwelling species be predicted in northern boreal forests? *Ecological Indicators,* **6**, 686–700.

Teketay, D., Kashe, K., Madome, J., Kabelo, M., Neelo, J., Mmusi, M. & Wellington, M. (2018) Enhancement of diversity, stand structure and regeneration of woody species through area exclosure: the case of a mopane woodland in northern Botswana. *Ecological Processes*, **7**, 5.

Teixeira, J.B. (1968) Parque Nacional do Bicuar, Carta da Vegetação (1ª Aproximação) e Memória Descritiva. Instituto de Investigação Agronómica de Angola, Nova Lisboa.

Wallenfang, J., Finckh, M., Oldeland, J. & Revermann R. (2015) Impact of shifting cultivation on dense tropical woodlands in southeast Angola. *Tropical Conservation Science*, **8**, 863–892.

Table 2: Vegetation classification of the woody vegetation of Huíla province based on 1 000 m² vegetation plots. The 465 table displays the indicator species of 466 every vegetation community identified in the analysis. Species are ordered according to Pearson's phi coefficient of association p <= 0.05. The phi value 467 ranges from 0 to 100, where phi > 30 is regarded as diagnostic of tree species. Species can be associated with more than one group or group combinations. 468 Only species with p ≤ 0.05 are shown in the table.

Vegetation Communities	1	2	3	4	5	6	7	8	9	10	11	12	13	1+2	1+4	2+3	2+5	2+6+7	12+13	*p-value*
Community 1: *Brachystegia spiciformis - Parinari curatellifolia* woodlands																				
Brachystegia boehmii	90														71					0.001
Parinari curatellifolia	86													69						0.001
Brachystegia spiciformis	83													82				100		0.001
Uapaca kirkiana	76													44						0.001
Brachystegia floribunda	72																			0.001
Brachystegia longifolia	72																			0.001
Syzygium guineense	69													51						0.001
Anisophyllea boehmii	62													41						0.001
Faurea rochetiana	62													36						0.001
Bobgunnia madagascariensis	62													49						0.001
Albizia antunesiana	55																			0.001
Uapaca nitida var. *nitida*	55																			0.001
Burkea africana	55																			0.001
Monotes africanus	41																			0.001
Bridelia mollis	41																			0.01
Pterocarpus angolensis	31																			0.01
Community 2: *Julbernardia paniculata-Brachystegia spiciformis* woodlands																				
Julbernardia paniculata		92														100	97	92		0.001
Brachystegia spiciformis		82																		0.001
Bobgunnia madagascariensis		49																		0.01
Uapaca kirkiana		44																		0.001
Syzygium guineense		51																		0.001
Faurea rochetiana		36																		0.001
Combretum collinum		36																36		0.01
Community 3: *Brachystegia longifolia-Diospyros kirkii* woodlands																				
Brachystegia longifolia			100																	0.001
Diospyros kirkii			66																	0.001
Pseudolachnostylis maprouneifolia subsp. *dekindtii*			62																	0.001
Dombeya rotundifolia			59																	0.001
Ekebergia benguellensis			45																	0.001
Bridelia micrantha var. *micrantha*			38																	0.001
Cussonia angolensis			31																	0.001
Vitex madiensis subsp. *madiensis*			31																	0.001
Bobgunnia madagascariensis			72																	0.001
Community 4: *Combretum collinum-Pericopsis angolensis* woodlands																				
Combretum collinum				86																0.001
Pericopsis angolensis				69																0.001
Diplorhynchus condylocarpon				63																0.001
Baphia bequaertii				55																0.001
Bridelia mollis				51																0.001
Combretum zeyheri				47																0.001
Phyllanthus reticulatus				47																0.001
Rothmannia engleriana var. *engleriana*				41																0.001
Community 5: *Julbernardia paniculata-Diplorhynchus condylocarpon* woodlands																				
Julbernardia paniculata					97															0.001
Diplorhynchus condylocarpon					83															0.001
Pseudolachnostylis maprouneifolia subsp. *dekindtii*					57															0.01
Brachystegia boehmii					51															0.01
Diospyros kirkii					49															0.001
Community 6: *Julbernardia paniculata-Combretum collinum* woodlands																				
Julbernardia paniculata						92														0.001
Combretum collinum						36														0.001
Community 7: *Brachystegia spiciformis-Pteleopsis anisoptera* woodlands																				
Brachystegia spiciformis							100													0.001
Pteleopsis anisoptera							58													0.01
Julbernardia paniculata							31													0.001

Vegetation Communities	1	2	3	4	5	6	7	8	9	10	11	12	13	1+2	1+4	2+3	2+5	2+6+7	12+13	*p-value*
Community 8: *Julbernardia paniculata-Burkea africana* woodlands																				
Burkea africana								50												0.001
Julbernardia paniculata								30												0.001
***Community 9: Hexalobus monopetalus-Pteleopsis anisoptera* woodlands**																				
Hexalobus monopetalus									42											0.001
Pteleopsis anisoptera									33											0.01
Commiphora mollis									31											0.001
Community 10: *Baikiaea plurijuga-Baphia massaiensis* woodlands																				
Baikiaea plurijuga										100										0.001
Baphia massaiensis subsp. *obovata*										63										0.001
Community 11: *Baphia massaiensis-Terminalia sericea* woodlands																				
Baphia massaiensis subsp. *obovata*											80									0.001
Terminalia sericea											70									0.001
Community 12: *Colophospermum mopane-Spirostachys africana* woodlands																				
Colophospermum mopane												90							84	0.001
Spirostachys africana												62								0.001
Terminalia prunioides												62							42	0.001
Acacia nilotica												45								0.001
Community 13: *Colophospermum mopane-Pterocarpus lucens* subsp. *antunesii* woodlands																				
Colophospermum mopane													84							0.001
Acacia nilotica													58							0.001
Commiphora mollis													53							0.001
Kirkia acuminata													53							0.001
Pterocarpus lucens subsp. *antunesii*													42							0.001
Commiphora angolensis													37							0.001
Croton mubango													32							0.01

References [CrossRef]

Azani, N., Babineau, M., Bailey, C.D., et al. (2017) A new subfamily classification of the Leguminasae based on a taxonomically comprehensive phylogeny. *Taxon*, **66,**44–77. CrossRef

Azevedo, A.L., Refrega, A.A.G., Sousa, E.C., et al. (1972). Caracterização Sumária das Condições Ambientais de Angola. Cursos Superiores de Agronomia e de Silvicultura, Universidade de Luanda, Nova Lisboa, Angola.

Banda, T., Schwartz, M.W. & Caro, T. (2006) Woody vegetation structure and composition along a protection gradient in a miombo ecosystem of western Tanzania. *Forest Ecology and Management*, **230**, 179–185. CrossRef

Banda, T., Mwangulango, N., Meyer, B. et al. (2008) The woodland vegetation of the Katavi-Rukwa ecosystem in western Tanzania. *Forest Ecology and Managemnet*, **255**, 3382–3395. CrossRef

Barbosa, L.A.G. (1970). Carta Fitogeográfica de Angola. Instituto de Investigação Científica de Angola. Oficinas Gerais de Angola, Luanda, Angola.

Barker, N., Clark, R., Maiato, F., Francisco, D., Neef, G. & Goyder D. (2015). Learning the ABCs: Angolan botanical collecting Part 2: Bush pilots and old volcanoes. *Veld & Flora*, **101**, 116–119.

Burgess, N., Hales, J.D., Underwood, E. et al. (2004) *Terrestrial ecoregions of Africa and Madagascar*. World Wildlife Fund (WWF). Island Press, Washington, DC.

Byers, A.B. (2001) *Conserving the miombo ecoregion*. Reconnaissance Summary. WWF, Southern Africa Regional Program Office, Harare, Zimbabwe.

Cabral, A.I.R., Vasconcelos, M.J., Oom, D. & Sardinha R (2011) Spatial dynamics and quantification of deforestation in the central-plateau woodlands of Angola (1990–2009). *Applied Geography*, **31**, 1185–1193. CrossRef

Chidumayo, E.N. (2002) Changes in miombo woodland structure under different land tenure and use systems in central Zambia. *Journal of Biogeography*, **29**, 1619–1626. CrossRef

Coates Palgrave, M. (2005) *Keith Coates Palgrave: Trees of Southern Africa*. Edn 3. Struik Publishers, Cape Town, South Africa.

De Cauwer, V., Geldenhuys, C. J., Aerts, R., Kabajani, M., & Muys, B. (2016). Patterns of forest composition and their long-term environmental drivers in the tropical dry forest transition zone of southern Africa. *Forest Ecosystems*, **3**, 23. CrossRef

dos Santos, R.M. (1982) *Itinerários florísticos e carta da vegetação do Cuando Cubango*. Instituto de Investigação Científica Tropical/Junta de Investigações Científicas do Ultramar, Lisboa, Portugal.

Figueiredo, E., & Smith, G.F. (2008). *Plants of Angola/Plantas de Angola*. South African National Biodiversity Institute, Pretoria, South Africa.

Furley, P.A., Rees, R.M., Ryan, C.M. & Saiz, G. (2008) Savanna burning and the assessment of long-term fire experiments with particular reference to Zimbabwe. *Progress in Physical Geography*, **32**, 611–634. CrossRef

Giliba, R.A., Boon, E.K., Kayombo, C.J., Musamba, E.B., Kashindye, A.M. & Shayo, P.F. (2011) Species composition, richness and diversity in miombo woodland of Bereku Forest Reserve Tanzania. *Journal of Biodiversity*, **2**, 1–7. CrossRef

Gonçalves, F.M.P. (2009) Contribuição para o conhecimento, distribuição e conservação da flora da Província da Huíla. Tese de Licenciatura. CrossRef

Gonçalves, F.M.P. & Goyder, D.J. (2016). A brief botanical survey into Kumbira forest, an isolated patch of Guineo-Congolian biome. *Phytokeys*, **65**, 1–14. CrossRef

Gonçalves, F.M.P., Revermann, R., Gomes, A.L., Aidar, M.P.M., Finckh, M. & Juergens, N. (2017) Tree species diversity and composition of miombo woodlands in south-central Angola: A chronosequence of forest recovery after shifting cultivation. *International Journal of Forest Research*, **2017**, 1–13. CrossRef

Gonçalves, F.M.P., Revermann, R., Cachissapa, M.J., Gomes, A.L., & Aidar, M.P.M. (2018) Species diversity, population structure, and regeneration of woody species in fallows and mature stands of tropical woodlands of Southeast Angola. *International Journal of Forest Research*, **2018**, 1–11.

Huntley, B. (1974a) Outlines of wildlife conservation in Angola. *Journal of the South African Wildlife Management Association*, **4**, 157–166.

Huntley, B.J. & Matos, E.M. (1994) Botanical diversity and its conservation in Angola. *Strelitzia* 1, Pretoria, South Africa.

Köppen, W. (1936). Handbuch der Climatologie, Ed. *Koppen Geiger*.

Kindt, R. & Coe R. (2005). *Tree diversity analysis: A manual and software for common statistical methods for ecological and biodiversity studies*. World Agroforestry Centre, Nairobi, Kenya.

Makhado, R.A., Mapaure, I., Potgieter, M.J., Luus-Powell, W.J. & Saidi, A.T. (2014) Factors influencing the adaptation and distribution of *Colophospermum mopane* in southern Africa's mopane savannah: A review. *Bothalia*, **44**, 1–9. CrossRef

Maiato, F. & Sweet, R.J. (2011) Guia de Pasto nas Áreas de Transumância, Angola. Manuais Transumância, GFA Consulting Group, Luanda, Angola.

Menezes, A. (1971) Estudo Fito-ecológico da região do Mucope e Carta da Vegetação. Sep. do Bol. Inst. Invest. Cient. Ang., Luanda, Angola.

Munishi, K.T., Temu, R.A.P.C., Soka, G. (2011) Plant communities and tree species associations in a miombo ecosystem in the Lake Rukwa basin, southern Tanzania: Implications for conservation. *Journal of Ecology and the Natural Environment* **3**, 63–71.

Mwakalukwa, E.E., Meilby, H. and Treue, T. (2014) Floristic composition, structure, and species associations of dry miombo woodland in Tanzania. *International Journal of Forest Research*, **2014**, 1–15. CrossRef

R Development Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Revermann, R. & Finckh, M. (2013) Okavango Basin: Vegetation. *Biodiversity & Ecology*, **5**, 29–35. CrossRef

Revermann, R., Oldeland, J., Gonçalvess, F.M., Luther-Mosebach, J., Gomes, A.L., Juergens, N. & Finckh, M. (2018) Dry tropical forests and woodlands of the Cubango Basin in southern Africa: A first classification and assessment of their woody species diversity. *Phytocoenologia*, **48**, 23–50. CrossRef

Röder, A., Pröpper, M., Stellmes, M., Schneibel, A., & Hill, J. (2016). Reprint of "Assessing urban growth and rural land use transformations in a cross-border situation in Northern Namibia and Southern Angola." *Land Use Policy*, ***53***, 97–111. CrossRef

Schmidtlein, S., Tichý, L., Feilhauer, H., Faude, U. (2010) A brute-force approach to vegetation classification. *Journal of Vegetation Science*, **21**, 1162–1171. CrossRef

Schneibel, A., Frantz, D., Röder, A., Stellmes, M., Fischer, K., & Hill, J. (2017) Using annual landsat time series for the detection of dry forest degradation processes in south-central Angola. *Remote Sensing*, **9**, 905. CrossRef

Simila, M., Kouki, J., Mönkkönen, M., Sippola, A. & Huhta, E. (2006) Co-variation and indicators of species diversity: Can richness of forest-dwelling species be predicted in northern boreal forests? *Ecological Indicators*, **6**, 686–700. CrossRef

Teketay, D., Kashe, K., Madome, J., Kabelo, M., Neelo, J., Mmusi, M. & Wellington, M. (2018) Enhancement of diversity, stand structure and regeneration of woody species through area exclosure: the case of a mopane woodland in northern Botswana. *Ecological Processes*, **7**, 5. CrossRef

Teixeira, J.B. (1968) Parque Nacional do Bicuar, Carta da Vegetação (1ª Aproximação) e Memória Descritiva. Instituto de Investigação Agronómica de Angola, Nova Lisboa.

Wallenfang, J., Finckh, M., Oldeland, J. & Revermann R. (2015) Impact of shifting cultivation on dense tropical woodlands in southeast Angola. *Tropical Conservation Science*, **8**, 863–892. CrossRef

Seasonal changes of biodiversity patterns and habitat conditions in a flooded savanna – The Cameia National Park Biodiversity Observatory in the Upper Zambezi catchment, Angola

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Abstract: Eastern Angola and western Zambia are dominated by the Zambezi catchment, where high precipitation and a dense river network cause annual flooding of extensive areas from January to ¬May. Cameia National Park in Angola is such a seasonally flooded savanna. A SASSCAL Biodiversity Observatory was established in May 2016, as little is known about the area's particular flora and fauna. Based on three visits to the observatory, we present a first description of the ecology of this dynamic ecosystem, its vegetation units and plant species, occurrence and turnover of bird assemblages, and human land-use practices. We observed that the turnover in species composition, temporal niches of functional groups and guilds, and land uses are controlled by seasonally changing flood, fire, and precipitation patterns. Our results highlight the conservation value of the area; sustainable management plans and conservation strategies are urgently needed to restore the formerly dominant herbivore guilds and to prevent destructive agro-industrial development schemes.

Resumo: Angola Oriental e Zâmbia Ocidental são dominadas pela bacia hidrográfica do Zambezi, onde a alta precipitação e a densa rede fluvial causam inundações anuais de extensas áreas entre os meses de Janeiro e Maio. O Parque Nacional da Cameia em Angola tem as suas savanas inundadas sazonalmente. Foi estabelecido em Maio de 2016 um Observatório de Biodiversidade do SASSCAL, já que pouco se sabe sobre a sua flora e fauna particulares. Com base em três visitas ao observatório, apresentamos uma primeira descrição da ecologia deste ecosistema dinâmico, das suas unidades de vegetação e espécies de plantas, da ocorrência e rotatividade de conjuntos de aves, e das prácticas humanas de uso das terras. Observámos que a rotatividade da composição de espécies, os nichos temporários de grupos funcionais e guildas, e o uso das terras são controlados pelos regimes sazonais de inundações, fogos e precipitação. Os nossos resultados realçam o valor de conservação da área; são urgentemente necessários planos de gestão sustentáveis e estratégias de conservação, de modo a recuperar as guildas de herbívoros outrora dominantes e prevenir esquemas destrutivos de desenvolvimento agro-industrial.

Introduction

Seasonally flooded savannas are dynamic landscapes that occur particularly in the South American and African tropics. Iconic examples are the Pantanal in Brazil, Paraguay, and Bolivia; the Llanos of Venezuela and Colombia; the Lake Chad region in West Africa; and the catchment area of the Upper Zambezi in Angola and Zambia. In such regions, plane landscapes with slowly draining rivers, impermeable soil layers, and high annual precipitation provide conditions that contribute to annual flooding (Junk & Furch, 1993; Welcomme, 1979). These ecosystems are home to specialized plants and animals, thus representing a particular biodiversity (Ward, 1998). Concurrently, humans make use of the flooding cycle by fishing in the flood season and grazing their cattle in the dry period (Abbott et al., 2007).

While other flooded savannas have already been the target of extensive studies, little is known about the species richness and ecology of seasonally flooded grasslands in south-central Africa. In particular, the still largely natural Zambezi catchment in Angola and Zambia lacks data as a result of difficult accessibility and the long-lasting civil war in Angola. The intactness and functionality of the ecosystems are, however, essential on a local as well as a continental scale, as the middle and lower reaches of the Zambezi River provide livelihoods for millions of people (Chenje et al., 2000; Emerton, 2003; Turpie et al., 1999). Therefore, to study and monitor biodiversity in the area and gain knowledge on land use and ecosystem function, we implemented a biodiversity observatory according to the BIOTA Africa standard (Jürgens et al., 2012) in Cameia National Park, Moxíco Province, in eastern Angola, in May

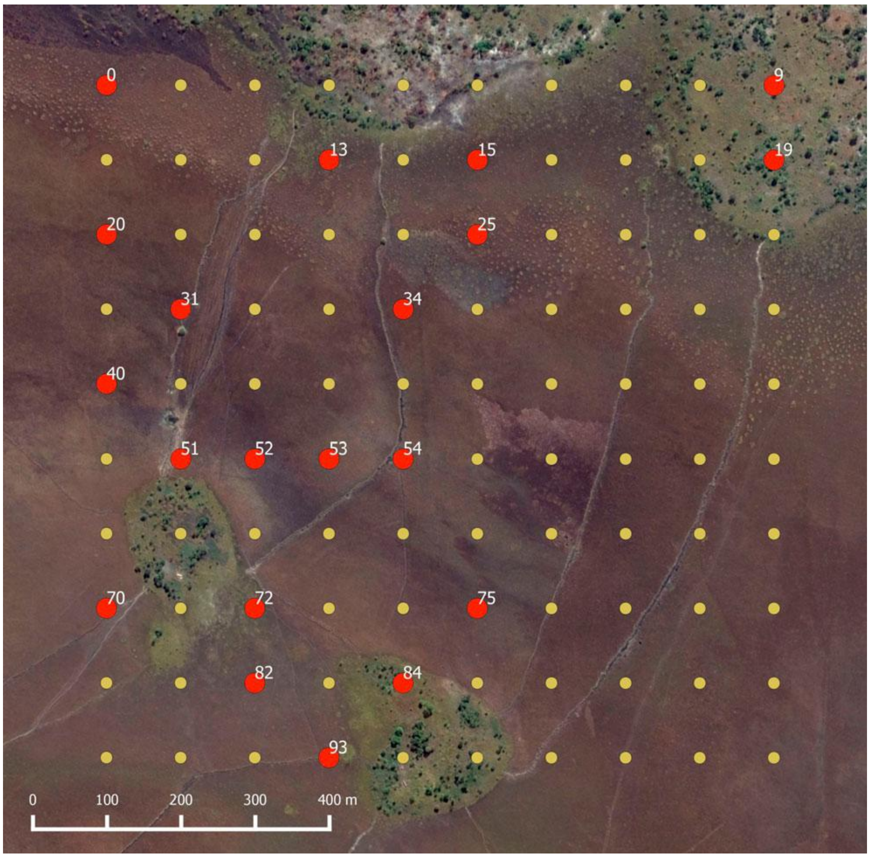

Figure 1: Observatory S76 in Cameia National Park. Fish dams between the woodland islands are clearly visible. Suffrutex grasslands surrounding the woodland patches are visible by the point pattern of termite mounds, which are not present in the flooded grasslands. Red dots mark the center points of the permanent plots. (Image source: Google Earth, 2014)

2016 (Hillmann et al., 2018; SASSCAL ObservationNet, 2017). This article summarizes initial insights into the ecology, plant and bird diversity, and human land use of Cameia National Park.

Our specific aims for this first assessment were to (a) gather preliminary information on habitat types, plant species richness, and diversity for the Cameia National Park Observatory S76 and (b) get a basic understanding of spatio-temporal niches for plants, animals, and human land use in this particular ecosystem, with its dramatic changes between dry and aquatic phases.

Methods

Study site

The eastern Moxico Province forms the major part of the Angolan headwaters of the Zambezi catchment. Its center is dominated by the extended sandy plains that characterize the landscapes of Cameia National Park. The western tributaries of the Zambezi flow in a southeasterly direction towards the Zambezi, cutting through the deposits of Kalahari sands with which the basin is filled (Wellington, 1955). Slightly elevated interfluves form wide plains intersected by small rivers. The fluvial beds in the Zambezi catchment tend to be meandering and swampy because of a low gradient that increases only after the river passes over Chavuma Falls at the Angolan-Zambian border (Nugent, 1990).

Observatory S76 is situated at the northern border of the national park (Fig. 1), between the villages Lumeje and Cassai Gare along the Benguela Railway, very close to the Great Equatorial Divide between the Zambezi and Congo catchments. It is subject to seasonal flooding, approximately from January to May, causing dynamic transitions between terrestrial and aquatic phases. As a consequence we observe, among other phenomena, temporal occurrence of fish, changing dominances in plant and birds communities, and changing land-use practices of local people. Grassland fires set by local communities after the flooded areas have dried out are a further seasonal disturbance.

Temperature recording

We used temperature loggers (Tinytag Plus 2, Gemini, UK) to assess microclimatic differences in various habitat types. Additionally, the data allowed us to infer the flooding period from buffered diurnal temperature fluctuations registered by inundated temperature sensors. We installed in total four loggers: (a) in low-lying grasslands that get inundated during the flood season, (b) 5 m from the first logger on a termitarium covered by grasses and geoxylic suffrutices (White, 1977; this vegetation type is hereafter referred to as suffrutex grassland), (c) in extended homogenous suffrutex grasslands and d) in open woodland. The loggers were buried with only the sensors protruding from earth, thus recording surface air temperatures close to the ground (0 cm–15 cm) at 15 min intervals from mid-November 2016 to the end of June 2017 (so far).

Vegetation survey

The installation of the observatory followed the standardized biodiversity observatory design of Jürgens et al. (2012). A 1 km² area was divided into a rectangular grid of 100 1 ha cells. The predominant vegetation unit and thus habitat type of each 1 ha cell was classified based upon visible vegetation structure in satellite images (Google Earth, 2014). Twenty 1 ha cells were selected according to a stratified sampling corresponding to the spatial cover of the four main vegetation units: woodland (three cells), suffrutex grassland (five cells), wet grassland (seven cells), and grassland (five cells) (see Fig. 1). In each of the selected cells, a 50 m x 20 m plot with a central 10 m x 10 m subplot was established. The surveys were conducted by recording species presence/absence in the whole plot plus their cover in the subplot. Since installation, the site has been visited three times: the first vegetation survey in May 2016 (dry season, flooded) was followed by another assessment in November 2016 (rainy season, dry) and a complementary collection of plant species in June 2017.

Bird observations

To complement the quantitative vegetation and flood phase surveys, we conducted opportunistic bird observations during each campaign and recorded bird species within the observatory. This encompassed mainly diurnal and conspicuous species identified by sight. However, our species lists were compared to and extended by the collection of specimens from Cameia National Park housed at the ornithological museum at ISCED Lubango. Furthermore, using the IBA species checklist (Leonard, 2010) of the comparable habitats from nearby Liuwa Plain National Park, Zambia, we compared species composition and overlap between the parks. This checklist, together with avifaunal information about Cameia National Park from BirdLife International (2017), was used to identify threatened and significant bird species. Finally, we categorized the observed bird species according to feeding guilds.

Land use

Information on the use of the landscape throughout the year by local communities was gathered by observations of human activity during the three field visits and informal conversations with members of local communities concerning their livelihoods and ways of life.

Results

Flood duration

The temperature curves recorded by our loggers indicate that the main flood season 2017 was from January to May, which is evident from buffered temperature oscillations at low-lying ground compared to more elevated sites (Fig. 2). The loggers on the slightly elevated termitarium in the flooded grassland, in the homogenous suffrutex grassland, and in the open woodlands did not show any phase of inundation. The water depths in the grasslands reached approximately 0.5 m but can be deeper locally in permanent pools or where earthen dams made for fishing purposes (see below) retain water. Temperatures in all vegetation units reach their maximum at noon and are lowest shortly before sunrise (6:00 a.m.). While the amplitudes were comparable between woodlands, suffrutex grasslands, and low-lying grasslands (grassland and wet grassland) in the early dry season (June), ranging diurnally between 10 °C and 37 °C, microclimatic differences were evident in the rainy and flooded season (March). In woodlands, temperatures range between 18 °C and 38 °C, in suffrutex grasslands from 22 °C to 42 °C, and in flooded grasslands from 26 °C to 36 °C during the day.

Vegetation survey

According to the initial vegetation unit classification based on satellite imagery of 100 ha cells in the observatory, the units are distributed and characterized as follows: slight sandy elevations above the flood level are covered by woodlands (ca. 13%; Fig. 3), their ecotones are subject to high rising ground water tables and host suffrutex grasslands (24%; Fig. 4), and the remaining 63% of the observatory corresponds to seasonally flooded savanna (grassland and wet grassland) (Fig. 5 and 6).

In the first vegetation assessment in May 2016, we recorded 215 different

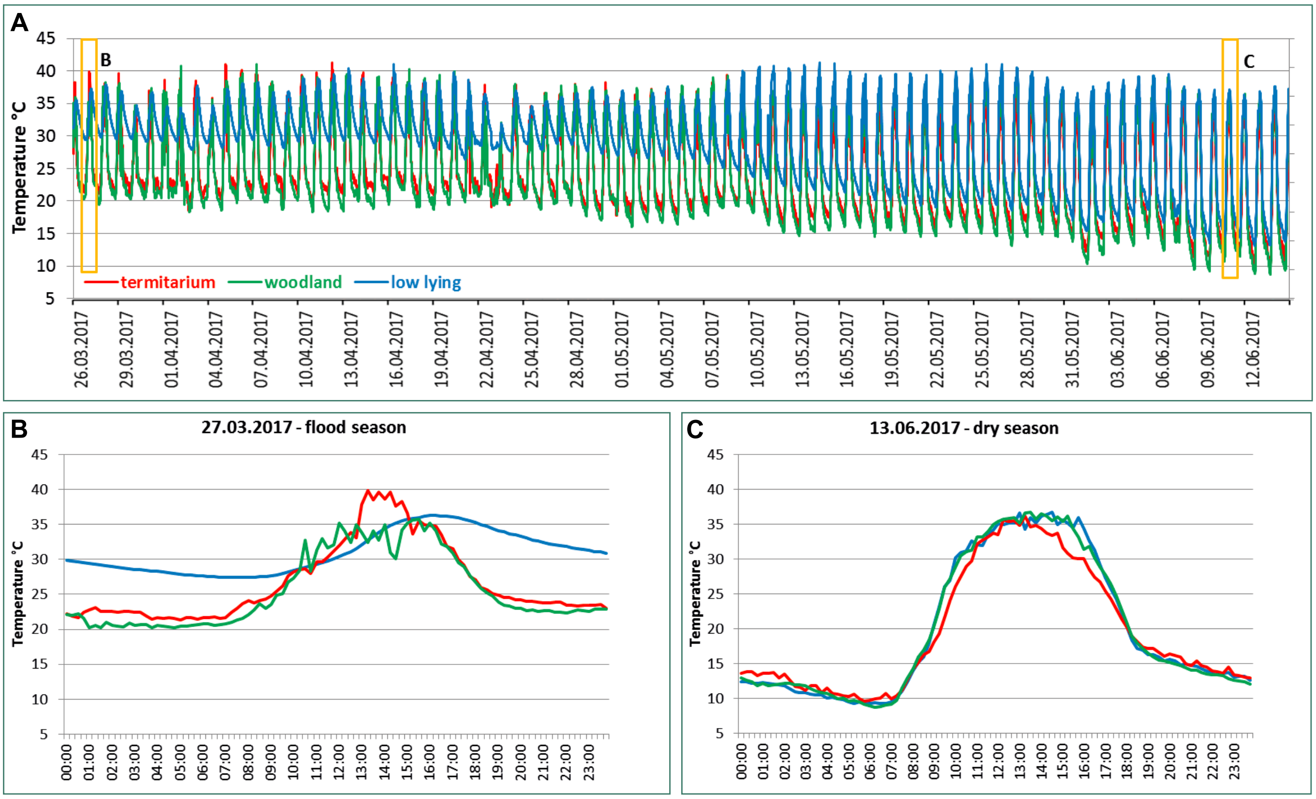

Figure 2: Ground temperature comparison of seasonally flooded savanna (blue line, logger a), an elevated termitaria within (red line, logger b), and surrounding open woodland (green line, logger d) from 26 March to 14 June 2017 in Cameia National Park (A). During the flood season (27 March 2017), the temperatures of inundated sites differ strongly from those of elevated or woodland sites. The water body buffers daily temperature fluctuations (lower and smoother amplitude of the blue line) (B). On the other hand, all temperature curves are comparable in the dry season (13 June 2017) and show similarly high amplitudes between cold morning and hot afternoon (C).

plant species in the whole observatory and in the second survey in November 2016, 167 different species were found. By the end of the third sampling in June 2017, we had counted more than 270 individual plant species within our 1 km² observatory, of which many are still waiting for identification. Figure 7 shows the mean seasonal species counts in the 100 m² subplots for each vegetation unit.

In the seasonally flooded plots, the plant communities differed most strongly between the early dry season (flooded phase) and the early rainy season (terrestrial phase), whereas the dominant communities in the woodland and suffrutex grassland plots (namely, woody species) did not show such strong seasonal floristic changes.

In the woodlands at elevated sites and islets, we observed the following dominant tree species: *Monotes glaber, Cryptosepalum exfoliatum* subsp. *pseudotaxus, Syzygium guineense* subsp. *guineense*, *Pterocarpus angolensis, Burkea africana, Bobgunnia madagascariensis, Uapaca gossweileri, U. robynsii, Erythrophleum africanum, Baphia massaiensis, Parinari curatellifolia, Pericopsis angolensis Brachystegia longifolia*, and *B. bakeriana*. In our observatory, trees start resprouting and flowering in mid-August/early September and keep their foliage until June. Leaves are then shed as the dry season begins. Once enough dry fuel is present, the fire season starts. Grass species in the open woodlands start flowering (and closing the ground layer) from January onwards and dominate the ground layer until the fire season starts. Commonly occuring grass species include *Andropogon eucomus* subsp. *huillense, Trachypogon spicatus, Monocymbium ceresiiforme*, and *Loudetia simplex*, and woodland-specific grass species are *Ctenium concinnum* and *Hyparrhenia rufa*.

The suffrutex grasslands at the fringes and ecotones between woodland and grassland show higher grass proportions than the woodlands with *Hyparrhenia* spp., *Digitaria* spp., and *Pogonarthria squarrosa* as well as several Cyperaceae and the abovementioned ubiquitous C4 grasses. Codominant with grasses are geoxylic suffrutices that start to resprout and flower at the peak of the dry season (mid-August/early September) after being burned. Occurring species include *Parinari capensis, Cryptosepalum exfoliatum* subsp. *suffruticans*, *Ochna*

Figure 3: Open woodland with patchy grass cover after a passage of fire. Photo: P. Zigelski, 2017.

Figure 4: Suffrutex grassland in the ecotones and on elevated termitaria within flooded plains. Photo: M. Finckh, 2016.

Figure 5: Grassland at the beginning of the rainy season in November, not yet inundated. Photo: P. Zigelski, 2016.

Figure 6: Approximately the same location in May, now fully flooded. Photo: P. Zigelski, 2016.

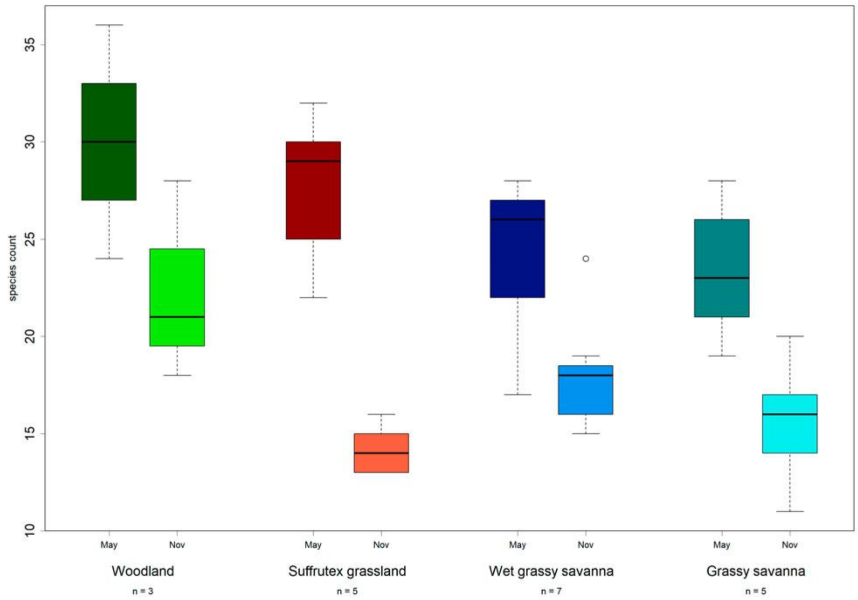

Figure 7: Mean species counts per vegetation unit and season in the 100 m² plots. Each unit is shown with its respective counts from May 2016 (darker box) and November 2016 (lighter box); whiskers indicate 1.5 times the interquartile range.

arenaria, Syzygium guineense subsp. *huillense, Magnistipula sapinii, Annona stenophylla* subsp. *nana, Eugenia malangensis, Anisophyllea quangensis,* and *Combretum platypetalum*. These geoxyles dominate the aspect of the suffrutex grassland until mid-rainy season (from mid-December onwards), when the C4 grasses start to develop their inflorescences and take over.

The grassland on lower ground is subject to seasonal flooding from January to May (see above) and lacks any woody species. These sites are dominated by hydrogeophytes and therophytes (e.g., *Nymphaea nouchali* var. *caerulea* and *Utricularia* spp.) during flooding, by small terrestrial therophytes (e.g., *Eriocaulon* spp., *Sebeae minuta, Burmannia madagascariensis, Drosera burkeana*, and *Utricularia pentadactyla*) when floods are receding (May–July), and by terrestrial geophytes such as *Ledebouria revoluta, Gladiolus* sp., *Heterotis canescens*, and *Polygala* sp. which survive the flooding but whose aboveground biomass development is reset by burning. Other perennial species include Cyperaceae such as *Eleocharis* sp., *Fuirena* sp., and *Rhynchospora* sp., several Xyridaceae, and a diversity of grass species, particularly *Microchloa kunthii, Andropogon eucomus* ssp. *huillense*, *Trachypogon spicatus*, *Monocymbium ceresiiforme*, and *Loudetia simplex*, which all seem to be well adapted to flooding.

Grasslands of similar species composition occur at midground, though these sites have shorter inundation periods. Their species numbers are slightly higher, but the dominant species and their phenology are similar to those of the lower ground.

Bird observations

So far, after three visits to the observatory, we have recorded 79 different bird species. Species composition and dominance differs strongly with seasonal change. Generalist and resident woodland or grassland species such as doves and pigeons (Cape turtle dove *Streptopelia capicola*, African green pigeon *Treron calvus*), crows (pied crow *Corvus albus*, Cape crow *C. capensis*) and fork-tailed drongos (*Dicrurus adsimilis*) occur throughout the year in their respective habitats. Birds of prey (e.g., brown snake eagle *Circaetus cinereus*, black-chested snake eagle *C. pectoralis*, dark chanting goshawk *Melierax metabates*, martial eagle *Polemaetus bellicosus*, bateleur *Terathopius ecaudatus*, white-headed vulture *Trigonoceps occipitalis*) have also been observed year-round but are most abundant and diverse in the early rainy season. At this time of year, as well as during receding flood, waders such as Temminck's stint *Calidris temminckii*, ruff *Philomachus pugnax*, and common greenshank *Tringa nebularia* occurred in the open grasslands and at pools.

With the onset of the flood season, aquatic species become dominant, particularly water fowl (e.g., spur-winged goose *Plectropterus gambensis*, hamerkop *Scopus umbretta*), egrets, cranes and storks (e.g., rufous-bellied heron *Ardeola rufiventris*, grey crowned crane *Balearica regulorum*, saddle-billed stork *Ephippiorhynchus senegalensis*), kingfishers (e.g., malachite kingfisher *Alcedo cristata*, African pygmy kingfisher *Ispidina picta*, giant kingfisher *Megaceryle maxima*) and other fish-feeding species (e.g., African fish eagle *Haliaeetus vocifer*).

Ground-dwelling species appear with receding flood and drying grasslands, particularly larks and pipits (e.g., Angolan lark *Mirafra angolensis*, Grimwood's longclaw *Macronyx grimwoodi*, dusky lark *Pinarocorys nigricans*), quails (e.g., harlequin quail *Coturnix delegorguei*), and bustards (e.g., black-bellied bustard *Lissotis melanogaster*, Denham's bustard *Neotis denhami*).

Seedeaters and insectivores were mainly observed in the flood phase, when grasses are fruiting and midges and mosquitos thrive over the water body. Among others, widowbirds (e.g., long-tailed widowbird *Euplectes progne*, fan-tailed widowbird *E. axillaris*), and waxbills and canaries (e.g., yellow-fronted canary *Serinus mozambicus*, common waxbill *Estrilda astrild*) are most conspicuous as well as chats (e.g., sooty chat *Myrmecocichla nigra*, capped wheatear *Oenanthe pileata*, common stonechat *Saxicola torquatus*), swallows (e.g. lesser striped swallow *Cecropis abyssinica*, Black-and-rufous swallow *Hirundo nigrorufa*, red-throated swallow *Petrochelidon rufigula*, grey-rumped swallow *Pseudhirundo griseopyga*), and cisticolas (e.g., zitting cisticola *Cisticola juncidis*).

In combination with the collection of bird specimens deposited at ISCED Lubango, Angola, we have counted so far a total of 209 different bird species recorded for Cameia National Park. In the structurally similar Liuwa Plain National Park in Zambia, 349 different bird species were recorded (Leonard, 2010), of which Cameia National Park shares 151 species (72.2%), though 58 species (27.8%) of the species occurring in Cameia National Park do not occur in Liuwa Plain National Park. According to the Zambian conservation categories, 14 species show a restricted range (Forbe's plover *Charadrius forbesi*, Dambo cisticola *Cisticola dambo*, Cape crow *Corvus capensis*, common quail *Coturnix coturnix*, lark-like bunting *Emberiza impetuani*, long-tailed widowbird *Euplectes progne*, greater kestrel *Falco rupicoloides*, red-throated wryneck *Jynx ruficollis*, Grimwood's longclaw *Macronyx grimwoodi*, Angola lark *Mirafra angolensis*, white-throated francolin *Peliperdix albogularis*, red-throated swallow *Petrochelidon rufigula*, black-chested prinia *Prinia flavicans*, whinchat *Saxicola rubetra*) and six species are threatened (grey crowned crane *Balearica regulorum*, African marsh harrier *Circus ranivorus*, slaty egret *Egretta vinaceigula*, saddle-billed stork *Ephippiorhynchus senegalensis*, Denham's bustard *Neotis denhami*, bateleur *Terathopius ecaudatus*). According to BirdLife International, five species that are poorly known or locally restricted occur in Cameia National Park: rufous-bellied heron *Ardeola rufiventris*, Forbe's plover *Charadrius forbesi*, brown firefinch *Lagonosticta nitidula*, white-throated francolin *Peliperdix albogularis*, and southern masked-weaver *Ploceus velatus*.

People and land use

Fish constitutes the main "cash crop" of the adjacent communities. The broad but very shallow flood channels in the plains are crisscrossed by small earthen dams (Fig. 1, Fig. 8) of about 1 m height, with multiple water outlets fitted with traditional fish traps made of grass stalks (Fig. 9). Fish migrate into the grasslands with rising water levels – and are harvested on their way back to the permanent water bodies. The catch is sun-dried on small wooden tables on the woodland islands (Fig. 10), where families build temporary huts for the fishing season. Dried fish is then transported in sacks and mostly on cargo bikes towards the larger marketplaces where middlemen buy the catches and sell the fish toward the urban centers of Angola.

Figure 8: Small earthen dams of about 1 m height crisscross the plains and serve for fish harvesting along the outlets. Photo: M. Finckh, 2016.

Figure 9: Fish traps made of grass stalks are inserted into the water outlets of earthen dams. Photo: M. Finckh, 2016.

Figure 10: Catch is sun-dried on small wooden tables on the woodland islands. Photo: M. Finckh, 2016.

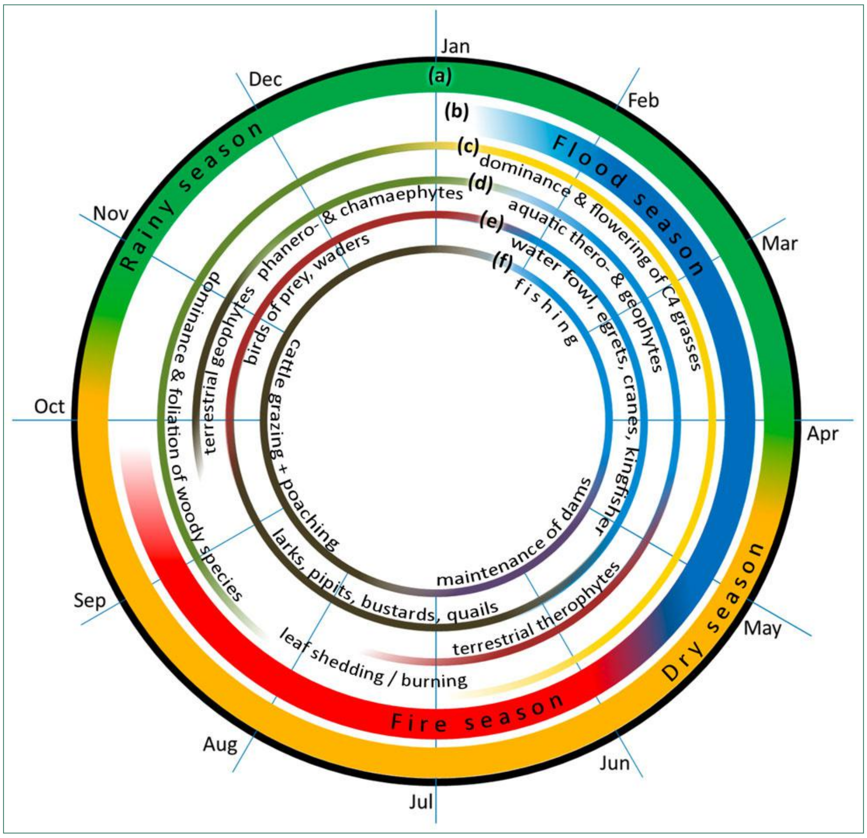

Figure 11: "Seasonal clock" of ecological events in Cameia National Park. The outer rings show the rainy and dry seasons (a) and the flood and fire seasons (b). The next ring (c) indicates the phenology of dominating perennial plant groups, and ring (d) describes the occurrence and dominance of seasonally limited plant groups. The inner rings show dominating or conspicuous bird groups (e) and the main practices of land use of local communities (f).

Fish dams are maintained and repaired at the beginning of the dry season, when soils are still humid and easy to dig. Fishing has an impact not only on the flooded areas but also on the habitats of the drier high ground. As dams are maintained and used by families, during the fishing season people settle temporarily in the small woodland islands and build small huts and the tables to dry the fish. This means that most of the small woodland patches are disturbed to a certain degree by woodcutting (for huts, tables, and firewood), debarking (for ropes), and the permanent presence of humans in areas which otherwise would be refugia for terrestrial fauna during the flooding season.

Cattle grazing is the main economic activity in the dry season. Shortly after the grasslands fall dry, around mid-June, people start to burn the grasslands, thus initiating the sprouting of the perennial C4 grasses. Once fresh grasses appear, adjacent communities start grazing their cattle on the grasslands close to the national park border or poach small game that is also attracted (Hall, 1984). Grazing goes on until flooding starts at the beginning of January, when cattle herding retreats to the reachable remaining high ground.

Currently there are no active fields within the observatory, but old fallows of former cassava plantations are recognizable in the woodlands. Google Earth images from 2002 indicate that cassava was produced there during the final phase of the civil war (e.g., on Plot 19, see Fig. 1).

Discussion

The vegetation surveys and bird observations both show seasonally changing species assemblages produced by changing environmental conditions. In addition, we observe different modes of land use by local communities throughout the year. The turnovers coincide with the seasonal change between flood, fire, dry, and rainy phases. These abiotic drivers hence control the prevalent assemblages and land-use activities (Fig. 11).

Flooding regime and origin

Based on buffered diurnal temperature fluctuations observed in the study (see Fig. 7), we see that the flood is delayed by about three months from the beginning of the rainy season (October to April; SASSCAL WeatherNet Station Mwinilunga in Zambia, 2017) (see Fig. 11 (a)/(b)). Flooding of the grasslands is thought to be a consequence of high precipitation in the catchment area (SASSCAL WeatherNet Station Mwinilunga: 1,400 mm/a), causing rising ground water tables on partly impermeable soil horizons within or below the leached sandy deposits (Welcomme, 1979; White, 1983). This leads to the apparently nutrient-poor waters, as indicated by numerous specialized carnivorous plant taxa such as Drosera spp. and Utricularia spp. Alternatively, in other parts of the national park, laterally overflowing rivers and streams probably also contribute to the inundation of the surrounding grasslands (Junk & Furch, 1993; Welcomme, 1979). While the latter, alluvial flooding type (Tockner & Stanford, 2002) is fairly well known and occurs for instance 400 km downstream the Zambezi at the Barotse Plains in Zambia (Moore et al., 2007) and at the Okavango Delta in Botswana (Wolski & Savenije, 2006), the rainfed sheet flooding is best described for savannas in South America such as the Llanos Baixos of the Orinoco basin in Venezuela (Godoy et al., 1999; Junk & Furch, 1993) or the Pantanal in Brazil (Alho, 2008). Thus, based on our observations on flooding pattern and species occurrences/preferences, we can show that similar systems also occur in Africa. During several flooded months, the water evaporates and slowly drains towards the tributaries of the Zambezi (review of the South American systems by Junk & Furch, 1993); only after the end of the rainy season do the surface waters drain off first and finally the ground water table drops, so that the ecosystem then switches into an extended terrestrial phase (June to December) (Fig. 11 (b)).

Responses in vegetation to the seasonal drivers

This flooding regime shapes the vegetation units and their species composition in the observatory. Most woody species avoid the waterlogged sites and are adapted to disturbance by fire (tree and suffrutex species in the ecotones and woodlands, such as *Burkea africana*) (Rutherford, 1981). Nonwoody perennials are adapted to flooding and fire (herb, grass, and sedge communities in the plains and under tree cover (Keeley & Rundel, 2005) (see Fig. 11 (c)).

Interestingly, with the beginning of the flood, aquatic therophytes and hydrogeophytes appear within the standing water body. After the water recedes it leaves behind wet, clayey-sandy patches between the grass tussocks, which are then occupied by semiterrestrial annuals (see Fig. 11 (d)) and geophytes. Thus, alternating life forms of annuals and (hydro-) geophytes subsequently use sophisticated spatial niches in this system dominated by bulky C4 grasses. In the case of the therophytes, first we find *Utricularia* spp. floating among the grass inflorescences, while later on semiterrestrial *Eriocaulon* spp. and other small sedges colonize the humid sands between the grass tufts. In a similar way, the space is first used by hydrogeophytes with their leaves floating among the grasses on the water surface (flooded phase: e.g., *Nymphaea* spp.), whereas after the flood terrestrial geophytes (e.g., *Gladiolus* sp., *Heterotis canescens*) start to flower between the grass tufts (see Fig. 12).

The number of recorded plant species was considerably higher in May than in November (see Fig. 7). This trend was evident in all four vegetation units, though the species counts in suffrutex grasslands differ more markedly. Since the low-lying areas (grassland and wet grassland) are still inundated in May, the aquatic species add to the species number in May and are not visible in November. The suffrutex grasslands benefit from the moist soil conditions in the second half of the rainy season, when the herbs and suffrutices are still visible and numerous small annual species and herbs are present (see Fig. 12). Similarly, species numbers in woodland units (particularly annuals) appear to be higher thanks to better water availability towards the end rather than in the first half of the rainy season. There is probably still a detection bias in our species data, however, as most of the perennial grasses only start to flower in January, so some grass species may have been overlooked in November. We furthermore expect the final plant species number to be higher since similar well-studied wetland ecosystems such as the Okavango Delta in Botswana present a much higher count (Ellery et al., 2000).

Seasonal change in bird species composition

Several bird groups, not only water-associated species, make use of the seasonal flooding (Fig. 11 (e)) as the inflowing water provides rich fishing grounds, attracts insect swarms, and promotes ripening and distribution of seeds and fruits (comparable to the wetlands in the Sahel; Zwarts et al., 2009). The small-scale heterogeneity of Cameia National Park allows for multiple aquatic guilds to coexist. Piscivorous birds, for instance, use the fishing dams and trees/shrubs at the trenches along the Benguela Railway and in the ecotones as lookout perches (African fish eagle *Haliaeetus vocifer*, giant kingfisher *Megaceryle maxima*), hover over the water surface (pied kingfisher *Ceryle rudis*), or stride through the water in the open plains (great egret *Ardea alba*). These aquatic guilds are at least local migrants, as their stay at Cameia National Park is temporally limited; little is known about their routes and where they stay after the flood, though it is likely that they withdraw to the vicinity of major perennial river runs (e.g., Zambezi). Soon after the flood recedes, terrestrial bird groups become dominant in the open plains. While larks and pipits require low vegetation strata, which they find in recently burned areas (Sinclair et al., 2010c,d), quails and bustards are attracted by standing grasses and use them for cover (Sinclair et al., 2010a,b). Thus, small-scale heterogeneity once more contributes to species richness, in this case as a consequence of anthropogenic, patchy burning of grasslands.

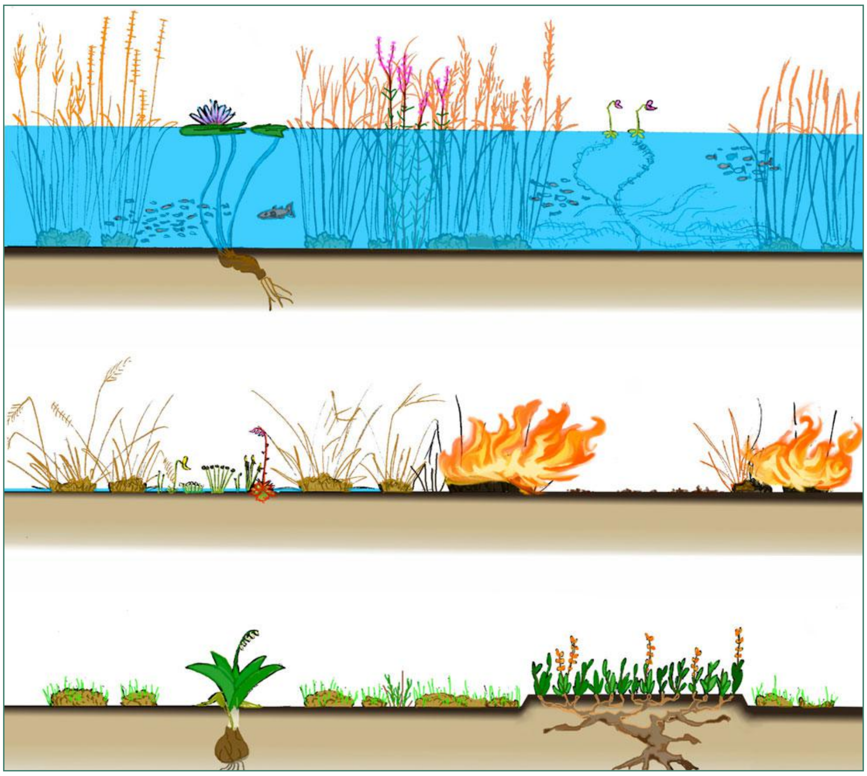

Figure 12: Schematic overview of the seasonal shifts from the aquatic to the terrestrial phases and the resulting dynamics of niches: (A) During the floods the space between perennial grasses (e.g., Andropogon eucomus subsp. huillense) and herbs (e.g., Heterotis canescens) is used by hydrogeophytes with floating leaves (e.g., Nymphaea nouchali var. caerulea) and therophytes (e.g., Utricularia benjaminiana). Fish and other small aquatic animals roam among the stalks. (B) Shortly after the flood, the still-moist soil between the tussocks offers niches for semiaquatic therophytes (Drosera sp., Eriocaulon spp.), which later burn away in the fire season. (C) Subsequently and with the beginning of the rainy season, terrestrial geophytes (particularly orchids and bulbous plants) start flowering between the resprouting C4 grasses. On higher ground (e.g., elevated termitaria) that is not inundated, geoxylic suffrutices (e.g., Parinari capensis) start to flower and develop their leaves. They dominate until the C4 grasses take over again from mid-December onwards.

Comparing the bird species composition and numbers to the famous Okavango Delta in Botswana or the Liuwa Plain in Zambia, we observe the same dominant families and guilds in these ecosystems. Though the recorded number of 209 species for Cameia National Park is much lower (Okavango Delta: 444 species; Liuwa Plain National Park: 349 species), nevertheless Accipitridae, Sylviidae, Ploceidae, and Ardeidae are particularly prevalent (African Parks, 2017; Leonard, 2010; Ramberg et al., 2006). This leads to the conclusion that either the Cameia National Park is severely impoverished with regard to bird species or, more likely, that data deficiency is great and more investigation is needed (see below).

Seasonal change in human land-use practices

The modes of human land use in Cameia National Park are another example of the use of spatially diverse and seasonally changing "resource niches" (see Fig. 11 (f)). In general, human land use has a major impact on landscape integrity and thereby on species diversity and composition in Africa (Anderson, 2014). However, and fortunately, in contrast to other protected areas in Angola (e.g., Mupa National Park and Quissama National Park), the seasonal flooding so far has prevented the encroachment of permanent settlements into the area. Nevertheless, the communities adjacent to Cameia National Park, mostly Chokwe, use the floodplains in multiple ways according to the season and certainly have influence on the flooding pattern (water-retaining fishing dams) and overall species composition (favoring species resilient to fire and cattle grazing) (Belsky, 1992). Next to the abiotic drivers shaping this particular ecosystem, human land use could hence be regarded as a biotic driver, affecting its species diversity and composition (see also below regarding mammals).

Outlook: Challenges for management and conservation

The Cameia National Park has formerly been home to high numbers of large vertebrates such as blue wildebeest Connochaetes taurinus, plains zebra Equus quagga, oribi Ourebia ourebi, lechwe Kobus leche, lion Panthera leo, cheetah Acinonyx jubatus, wild dog Lycaon pictus, and crocodile Crocodylus niloticus (Da Silva, 1952; Huntley, 1974). Indeed, not far away across the Zambian border, the seasonally flooded savannas of the Liuwa Plain National Park still teem with huge numbers of wildebeest, zebra, smaller antelopes, and the predators that hunt them (African Parks, 2017). The park is furthermore famous for its bird diversity (Leonard, 2010). Angola's national parks, however, suffered during the civil war from the mid-1960s to 2002, in which uncontrolled and heavily armed hunting brought most populations of large mammals to the point of collapse. Cameia National Park was no exception in this sense; the once-famous big migrations of tens of thousands of blue wildebeest and other larger herbivores have been wiped out.

No exact information is available about the current status of larger fauna in Cameia National Park; however, the park seems to be largely devoid of larger mammals. It is safe to assume that the elimination of the former herbivore guild has changed the food webs and nutrient dynamics in the grasslands considerably, but again, scientific studies are missing. The landscapes and the avifauna (and probably most of the smaller fauna) are, however, still pristine. There are probably few areas in Africa where so large unspoiled natural grasslands are still to be found, and the avifauna is still remarkable in species composition and seasonal shifts.

To conclude, our first results indicate the particularity of the ecosystems and their conservation value as well as the current conservation challenges for Cameia National Park, which arise from conflicting interests between sustainable ecosystem maintenance and growing human demands. Scientific data are almost nonexistent. Thus, there is an urgent need for studies of ecosystems and biodiversity in this area. This is particularly of interest since seasonally flooded grasslands in Africa are in general poorly studied (Turpie et al., 1999; Turpie, 2008) and new challenges for conservation are looming large. The provincial and the national governments favor economic development above conservation, and large-scale land conversion to industrial rice cropping and aquiculture is under discussion for Moxico (ANGOP, 2017), including parts of Cameia National Park. To assess possible effects for the park's unique ecosystems (e.g., in terms of direct conversion, changes in nutrient status of the waters, invasive fish species, etc.) a better understanding of the ecology, diversity, and resilience of this macro-ecosystem is urgently needed.

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References

Abbott, J.G., Campbell, L.M., Hay, C.J., Næsje, T.F. & Purvis, J. (2007) Market-resource links and fish vendor livelihoods in the upper Zambezi river floodplains. *Human Ecology*, **35**, 559–574.

African Parks (2017) Liuwa Plain National Park. https://www.african-parks.org/the-parks/liuwa-plain/fauna-flora (accessed 20/09/17)

Alho, C.J.R. (2008) Biodiversity of the Pantanal: Response to seasonal flooding regime and to environmental degradation. *Brazilian Journal of Biology*, **68**, 957–966.

Anderson, P.M.L. (2014) Regional assessment of Africa. *Urbanization, biodiversity and ecosystem services: A global assessment* (ed. by T. Elmqvist, M. Fragkias, J. Goodness, et al.), pp. 453–460. Springer, Berlin.

ANGOP, A.A.P. (2017) Moxico: Cameia prepara mais de mil hectares para cultivar arroz. http://www.angop.ao/angola/pt_pt/noticias/economia/2017/6/28/Moxico-Cameia-prepara-mais-mil-hectares-para-cultivar-arroz,be825477-10c7-472d-b6e3-cb1ed5d25974.html (accessed 22/08/17).

Belsky, A.J. (1992) Effects of grazing, competition, disturbance and fire on species composition and diversity in grassland communities. *Journal of Vegetation Science*, **3**, 187–200.

BirdLife International (2017) Important Bird Areas factsheet: Cameia National Park. http://datazone.birdlife.org/site/factsheet/cameia-national-park-iba-angola (accessed 28/09/17).

Chenje, M., SADC Environment and Land Management Sector, SADC Water Resources Sector, IUCN Regional Office for Southern Africa, India Musokotwane Environment Resource Centre for Southern Africa, Zambezi River Authority, International Union for Conservation of Nature and Natural Resources & Communicating the Environment Programme eds. (2000) *State of the environment 2000: Zambezi Basin*. SADC Environment and Land Management Sector, SADC Water Resources Sector Coordination Unit, IUCN Regional Office for Southern Africa, Southern African Research and Documentation Centre, Musokotwane Environment Resource Centre for Southern Africa, Zambezi River Authority, Maseru, Lesotho; Harare, Zimbabwe; Lusaka, Zambia.

Da Silva, S.N. (1952) Wild life and its protection in Angola. *Oryx*, **1**, 343–346.

Ellery, W., McCarthy, T. & Dangerfield, J. (2000) Floristic diversity in the Okavango Delta, Botswana as an endogenous product of biological activity. *Biodiversity in Wetlands: Assessment, Function and Conservation*, **1**, 195–225.

Emerton, L. (2003) *Barotse Floodplain, Zambia: Local economic dependence on wetland resources*. Case studies in wetland valuation no. 2, IUCN. https://www.cbd.int/financial/values/zambia-valuebarotse.pdf (accessed 06/05/2017).

Godoy, J.R., Petts, G. & Salo, J. (1999) Riparian flooded forests of the Orinoco and Amazon basins: A comparative review. *Biodiversity & Conservation*, **8**, 551–586.

Hall, M. (1984) Man's historical and traditional use of fire in southern Africa. *Ecological effects of fire in South African ecosystems* (ed. by P.V. de Booysen & N.M. Tainton), pp. 39–52. Springer, Berlin.

Hillmann, T., Muche, G., Josenhans, K. & Jürgens, N. (2018) Online presentation of the SASSCAL ObservationNet. This volume.

Huntley, B.J. (1974) Outlines of wildlife conservation in Angola. *South African Journal of Wildlife Research*, **4**, 157–166.

Junk, W.J. & Furch, K. (1993) A general review of tropical South American floodplains. *Wetlands Ecology and Management*, **2**, 231–238.

Jürgens, N., Schmiedel, U., Haarmeyer, D.H., Dengler, J., Finckh, M., Goetze, D., Gröngröft, A., Hahn, K., Koulibaly, A. & Luther-Mosebach, J. (2012) The BIOTA Biodiversity Observatories in Africa—A standardized framework for large-scale environmental monitoring. *Environmental Monitoring and Assessment*, **184**, 655–678.

Keeley, J.E. & Rundel, P.W. (2005) Fire and the Miocene expansion of C4 grasslands. *Ecology Letters*, **8**, 683–690.

Leonard, P. (2010) Zambian Important Bird Areas & National Parks Bird Checklists. http://www.birdwatchzambia.org/content/data.shtml & https://www.africanbirdclub.org/sites/default/files/Zambia_checklists.xls (accessed 20/10/2017).

Moore, A.E., Cotterill, F.P., Main, M.P. & Williams, H.B. (2007) The Zambezi River. *Large rivers: Geomorphology and management* (ed. by A. Gupta), pp. 311–332. John Wiley & Sons, Chichester, UK.

Nugent, C. (1990) The Zambezi River: Tectonism, climatic change and drainage evolution. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **78**, 55–69.

Ramberg, L., Hancock, P., Lindholm, M., Meyer, T., Ringrose, S., Sliva, J., Van As, J. & Vander Post, C. (2006) Species diversity of the Okavango Delta, Botswana. *Aquatic Sciences—Research across Boundaries*, **68**, 310–337.

Rutherford, M. (1981) Survival, regeneration and leaf biomass changes in woody plants following spring burns in *Burkea africana—Ochna pulchra* savanna. *Bothalia*, **13**, 531–552.

SASSCAL ObservationNet (2017) Cameia National Park (S76) - Infosheet. http://www.sasscalobservationnet.org/obs_details_obs.php?obs_id=S76 (accessed 16/08/17).

SASSCAL WeatherNet (2017) Mwinilunga climate data 2013–2017. http://www.sasscalweathernet.org/station_datasheet_we.php?loggerid_crit=856121 (accessed 16/08/17).

Sinclair, I., Ryan, P., Arlott, N., Hayman, P. & Harris, A. (2010a) Bustards. *Birds of Africa south of the Sahara* (ed. by I. Sinclair & P. Ryan), pp. 146–151. Struik Nature, Cape Town, South Africa.

Sinclair, I., Ryan, P., Arlott, N., Hayman, P. & Harris, A. (2010b) Francolins and quails. *Birds of Africa south of the Sahara* (ed. by I. Sinclair & P. Ryan), pp. 120–137. Struik Nature, Cape Town, South Africa.

Sinclair, I., Ryan, P., Arlott, N., Hayman, P. & Harris, A. (2010c) Larks and sparrowlarks. *Birds of Africa, South of the Sahara* (ed. by I. Sinclair & P. Ryan), pp. 328–349. Struik Nature, Cape Town, South Africa.

Sinclair, I., Ryan, P., Arlott, N., Hayman, P. & Harris, A. (2010d) Longclaws and pipits. *Birds of Africa, South of the Sahara* (ed. by I. Sinclair & P. Ryan), pp. 366–375. Struik Nature, Cape Town, South Africa.

Tockner, K. & Stanford, J.A. (2002) Riverine flood plains: Present state and future trends. *Environmental Conservation*, **29**, 308–330.

Turpie, J., Smith, B., Emerton, L. & Barnes, J. (1999) *Economic value of the Zambezi wetlands*. World Conservation Union (IUCN), Nairobi, Kenya.

Turpie, J.K. (2008) The valuation of riparian fisheries in Southern and Eastern Africa. *Tropical river fisheries valuation: Background papers to a global synthesis* (ed. by C. Bene), pp. 107–146. World Fish Center, Penang, Malaysia.

Ward, J. (1998) Riverine landscapes: Biodiversity patterns, disturbance regimes, and aquatic conservation. *Biological Conservation*, **83**, 269–278.

Welcomme, R.L. (1979) Hydrology. *Fisheries Ecology of Floodplain Rivers*, pp. 51–62. FAO, Rome.

Wellington, J.H. (1955) *Southern Africa: A geographical study. Part 1: Physical geography*, Cambridge University Press, Cambridge.

White, F. (1977) The underground forests of Africa: A preliminary review. *The Gardens' Bulletin,* (Singapore), **29**, 57–71.

White, F. (1983) *The vegetation of Africa: A descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa.* UNESCO, Paris.

Wolski, P. & Savenije, H.H.G. (2006) Dynamics of floodplain-island groundwater flow in the Okavango Delta, Botswana. *Groundwater-Surface Water Interactions in Wetlands for Integrated Water Resources Management*, **320**, 283–301.

Zwarts, L., Bijlsma, R.G., van der Kamp, J. & Wymenga, E. (2009) *Living on the edge: Wetlands and birds in a changing Sahel*. KNNV Publishing, Zeist, The Netherlands.

References [CrossRef]

Abbott, J.G., Campbell, L.M., Hay, C.J., Næsje, T.F. & Purvis, J. (2007) Market-resource links and fish vendor livelihoods in the upper Zambezi river floodplains. *Human Ecology*, **35**, 559–574. CrossRef

African Parks (2017) Liuwa Plain National Park. https://www.african-parks.org/the-parks/liuwa-plain/fauna-flora (accessed 20/09/17)

Alho, C.J.R. (2008) Biodiversity of the Pantanal: Response to seasonal flooding regime and to environmental degradation. *Brazilian Journal of Biology*, **68**, 957–966. CrossRef

Anderson, P.M.L. (2014) Regional assessment of Africa. *Urbanization, biodiversity and ecosystem services: A global assessment* (ed. by T. Elmqvist, M. Fragkias, J. Goodness, et al.), pp. 453–460. Springer, Berlin.

ANGOP, A.A.P. (2017) Moxico: Cameia prepara mais de mil hectares para cultivar arroz. http://www.angop.ao/angola/pt_pt/noticias/economia/2017/6/28/Moxico-Cameia-prepara-mais-mil-hectares-para-cultivar-arroz,be825477-10c7-472d-b6e3-cb1ed5d25974.html (accessed 22/08/17).

Belsky, A.J. (1992) Effects of grazing, competition, disturbance and fire on species composition and diversity in grassland communities. *Journal of Vegetation Science*, **3**, 187–200.

BirdLife International (2017) Important Bird Areas factsheet: Cameia National Park. http://datazone.birdlife.org/site/factsheet/cameia-national-park-iba-angola (accessed 28/09/17).

Chenje, M., SADC Environment and Land Management Sector, SADC Water Resources Sector, IUCN Regional Office for Southern Africa, India Musokotwane Environment Resource Centre for Southern Africa, Zambezi River Authority, International Union for Conservation of Nature and Natural Resources & Communicating the Environment Programme eds. (2000) *State of the environment 2000: Zambezi Basin*. SADC Environment and Land Management Sector, SADC Water Resources Sector Coordination Unit, IUCN Regional Office for Southern Africa, Southern African Research and Documentation Centre, Musokotwane Environment Resource Centre for Southern Africa, Zambezi River Authority, Maseru, Lesotho; Harare, Zimbabwe; Lusaka, Zambia.

Da Silva, S.N. (1952) Wild life and its protection in Angola. *Oryx*, **1**, 343–346.

Ellery, W., McCarthy, T. & Dangerfield, J. (2000) Floristic diversity in the Okavango Delta, Botswana as an endogenous product of biological activity. *Biodiversity in Wetlands: Assessment, Function and Conservation*, **1**, 195–225.

Emerton, L. (2003) *Barotse Floodplain, Zambia: Local economic dependence on wetland resources*. Case studies in wetland valuation no. 2, IUCN. https://www.cbd.int/financial/values/zambia-valuebarotse.pdf (accessed 06/05/2017).

Godoy, J.R., Petts, G. & Salo, J. (1999) Riparian flooded forests of the Orinoco and Amazon basins: A comparative review. *Biodiversity & Conservation*, **8**, 551–586. CrossRef

Hall, M. (1984) Man's historical and traditional use of fire in southern Africa. *Ecological effects of fire in South African ecosystems* (ed. by P.V. de Booysen & N.M. Tainton), pp. 39–52. Springer, Berlin. CrossRef

Hillmann, T., Muche, G., Josenhans, K. & Jürgens, N. (2018) Online presentation of the SASSCAL ObservationNet. *This volume*. CrossRef

Huntley, B.J. (1974) Outlines of wildlife conservation in Angola. *South African Journal of Wildlife Research*, **4**, 157–166.

Junk, W.J. & Furch, K. (1993) A general review of tropical South American floodplains. *Wetlands Ecology and Management*, **2**, 231–238. CrossRef

Jürgens, N., Schmiedel, U., Haarmeyer, D.H., Dengler, J., Finckh, M., Goetze, D., Gröngröft, A., Hahn, K., Koulibaly, A. & Luther-Mosebach, J. (2012) The BIOTA Biodiversity Observatories in Africa—A standardized framework for large-scale environmental monitoring. *Environmental Monitoring and Assessment*, **184**, 655–678. CrossRef

Keeley, J.E. & Rundel, P.W. (2005) Fire and the Miocene expansion of C4 grasslands. *Ecology Letters*, **8**, 683–690. CrossRef

Leonard, P. (2010) Zambian Important Bird Areas & National Parks Bird Checklists. http://www.birdwatchzambia.org/content/data.shtml & https://www.africanbirdclub.org/sites/default/files/Zambia_checklists.xls (accessed 20/10/2017).

Moore, A.E., Cotterill, F.P., Main, M.P. & Williams, H.B. (2007) The Zambezi River. *Large rivers: Geomorphology and management* (ed. by A. Gupta), pp. 311–332. John Wiley & Sons, Chichester, UK.

Nugent, C. (1990) The Zambezi River: Tectonism, climatic change and drainage evolution. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **78**, 55–69. CrossRef

Ramberg, L., Hancock, P., Lindholm, M., Meyer, T., Ringrose, S., Sliva, J., Van As, J. & Vander Post, C. (2006) Species diversity of the Okavango Delta, Botswana. *Aquatic Sciences—Research across Boundaries*, **68**, 310–337. CrossRef

Rutherford, M. (1981) Survival, regeneration and leaf biomass changes in woody plants following spring burns in *Burkea africana—Ochna pulchra* savanna. *Bothalia*, **13**, 531–552. CrossRef

SASSCAL ObservationNet (2017) Cameia National Park (S76) - Infosheet. http://www.sasscalobservationnet.org/obs_details_obs.php?obs_id=S76 (accessed 16/08/17).

SASSCAL WeatherNet (2017) Mwinilunga climate data 2013–2017. http://www.sasscalweathernet.org/station_datasheet_we.php?loggerid_crit=856121 (accessed 16/08/17).

Sinclair, I., Ryan, P., Arlott, N., Hayman, P. & Harris, A. (2010a) Bustards. *Birds of Africa south of the Sahara* (ed. by I. Sinclair & P. Ryan), pp. 146–151. Struik Nature, Cape Town, South Africa.

Sinclair, I., Ryan, P., Arlott, N., Hayman, P. & Harris, A. (2010b) Francolins and quails. *Birds of Africa south of the Sahara* (ed. by I. Sinclair & P. Ryan), pp. 120–137. Struik Nature, Cape Town, South Africa.

Sinclair, I., Ryan, P., Arlott, N., Hayman, P. & Harris, A. (2010c) Larks and sparrowlarks. *Birds of Africa, South of the Sahara* (ed. by I. Sinclair & P. Ryan), pp. 328–349. Struik Nature, Cape Town, South Africa.

Sinclair, I., Ryan, P., Arlott, N., Hayman, P. & Harris, A. (2010d) Longclaws and pipits. *Birds of Africa, South of the Sahara* (ed. by I. Sinclair & P. Ryan), pp. 366–375. Struik Nature, Cape Town, South Africa.

Tockner, K. & Stanford, J.A. (2002) Riverine flood plains: Present state and future trends. *Environmental Conservation*, **29**, 308–330. CrossRef

Turpie, J., Smith, B., Emerton, L. & Barnes, J. (1999) *Economic value of the Zambezi wetlands*. World Conservation Union (IUCN), Nairobi, Kenya.

Turpie, J.K. (2008) The valuation of riparian fisheries in Southern and Eastern Africa. *Tropical river fisheries valuation: Background papers to a global synthesis* (ed. by C. Bene), pp. 107–146. World Fish Center, Penang, Malaysia.

Ward, J. (1998) Riverine landscapes: Biodiversity patterns, disturbance regimes, and aquatic conservation. *Biological Conservation*, **83**, 269–278. CrossRef

Welcomme, R.L. (1979) Hydrology. *Fisheries Ecology of Floodplain Rivers*, pp. 51–62. FAO, Rome.

Wellington, J.H. (1955) *Southern Africa: A geographical study. Part 1: Physical geography*, Cambridge University Press, Cambridge.

White, F. (1977) The underground forests of Africa: A preliminary review. *The Gardens' Bulletin*, (Singapore), **29**, 57–71.

White, F. (1983) *The vegetation of Africa: A descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa.* UNESCO, Paris.

Wolski, P. & Savenije, H.H.G. (2006) Dynamics of floodplain-island groundwater flow in the Okavango Delta, Botswana. *Groundwater-Surface Water Interactions in*

Wetlands for Integrated Water Resources Management, **320**, 283–301. CrossRef
Zwarts, L., Bijlsma, R.G., van der Kamp, J. & Wymenga, E. (2009) *Living on the edge: Wetlands and birds in a changing Sahel*. KNNV Publishing, Zeist, The Netherlands.

Online presentation of the SASSCAL ObservationNet

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A network of Biodiversity Observatories

One of the challenges of interdisciplinary research is to consistently make available the data and products that have been developed in the individual disciplines and to guarantee their long-term availability. For this purpose, the website for the SASSCAL ObservationNet (http://www.sasscalobservationnet.org) was developed.

Biodiversity Observatories have been established as research infrastructures that allow the monitoring of the impact of climate and other environmental changes on biodiversity. Each observatory has a size of 1 km^2 and is subdivided according to the needs of disciplinary research, but all of them follow a standardized sampling design (Jürgens et al., 2012). The observatories are studied by researchers from various disciplines including botany, zoology, agriculture, mycology, climatology, meteorology, soil sciences, remote sensing, anthropology, and socio-ecology. Information on changes in the biosphere will be made available in a similar way, as meteorologists are already able to describe climate change (Pereira et al., 2013). In the frame of the Global Observation System of Systems (GEOSS, https://www.earthobservations.org/geoss.php) and its Global Biodiversity Observation Network (GEO BON, http://geobon.org), such plot-based observation sites are important research infrastructures.

Requirements for an Internet presentation

Presenting the complex data generated by the monitoring at Biodiversity Observatories is a challenge. Each observation, measurement, and visit must be assigned with respect to two parameters, location and time.

Features of the website

The network currently comprises 57 Biodiversity Observatories: 6 in Angola, 31 in Namibia, 17 in South Africa, and 3 in Zambia (Jürgens et al., 2018). Several of these were already established before the SASSCAL era as part of the BIOTA AFRICA project (Jürgens et al., 2010). Therefore, there are data and time series since 2001. As part of the SASSCAL initiative, the work continued on these Biodiversity Observatories, and new observatories, especially in Angola and Zambia, were added.

On the website, each individual Biodiversity Observatory is introduced with an information sheet showing a panoramic photograph and providing general information on the location, the landscape, and basic ecological facts. Additionally, biotic and environmental data and time series available for the observatory are listed (Fig. 1).

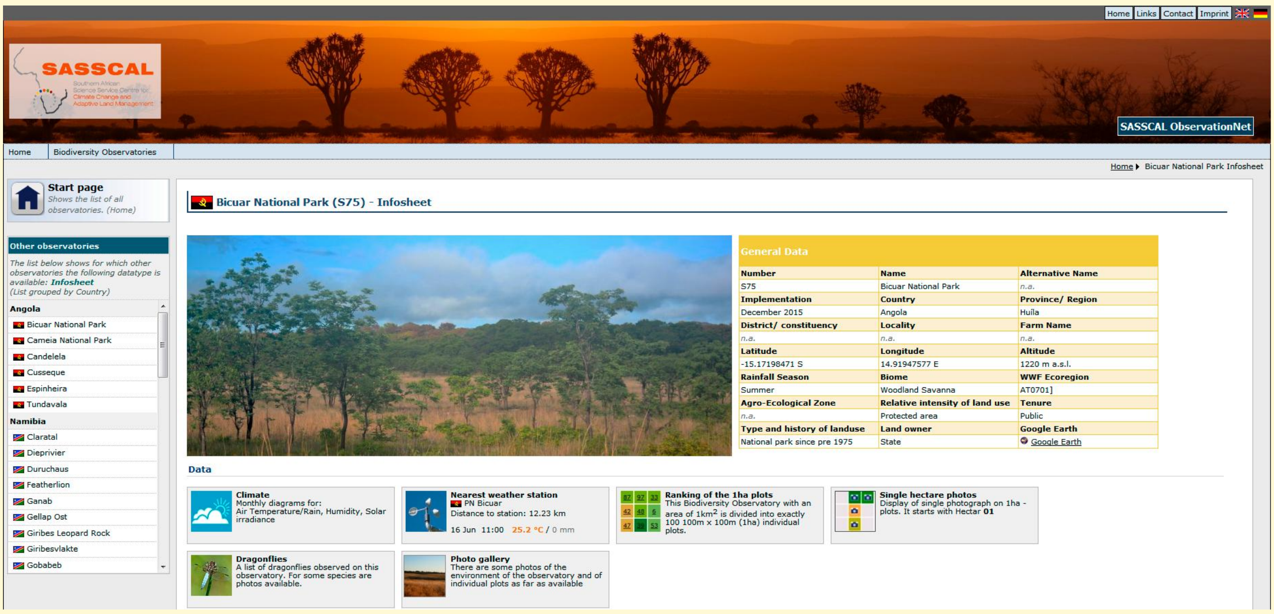

Figure 1: Infosheet for the Biodiversity Observatory, Bicuar National Park.

Different data types such as species checklists, tables, photographs, satellite images, and measurement series are provided (Fig. 2). The weather data offer a good example of how data can be associated to the observatories: Nearly every Biodiversity Observatory has a weather station installed. The SASSCAL ObservationNet website is permanently linked to the SASSCAL WeatherNet website (Muche et al., 2018). This link is used to display the time series of the weather data within the Biodiversity Observatories (Fig. 3).

Another link takes photographs of vascular plant species present at the observatory from the *Photo Guide to Plants of Southern Africa* (Hillmann et al., 2018) and embeds them in the SASSCAL ObservationNet website.

References

Hillmann, T., Muche, G., Josenhans, K. & Jürgens, N. (2018) SASSCAL Photo Guide to Plants of Southern Africa. This volume.

Jürgens, N., Haarmeyer, D.H., Luther-Mosebach, J., Dengler, J., Finckh & M., Schmiedel, U. (2010) *Biodiversity in southern Africa 1: Patterns at local scale – the BIOTA Observatories.* Klaus Hess Publishers, Göttingen & Windhoek.

Jürgens, N., Schmiedel, U., Haarmeyer, D.H. et al. (2012) The BIOTA Biodiversity Observatories in Africa — a standardized framework for large-scale environmental monitoring. *Environmental Monitoring and Assessment*, **184**, 655–678.

Jürgens, N., Strohbach, B., Lages, F., Schmiedel, U., Finckh, M., Sichone, P., Hahn, L.-M. & Zigelski, P. (2018) Biodiversity observation — an overview of the current state and first results of biodiversity monitoring studies. This volume.

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: present state, challenges, and achievements of the regional climatic observation network and database. This volume.

Pereira, H.M., Ferrier, S., Walters, M. et al. (2013) Essential biodiversity variables. *Science*, **339**, 277-278.

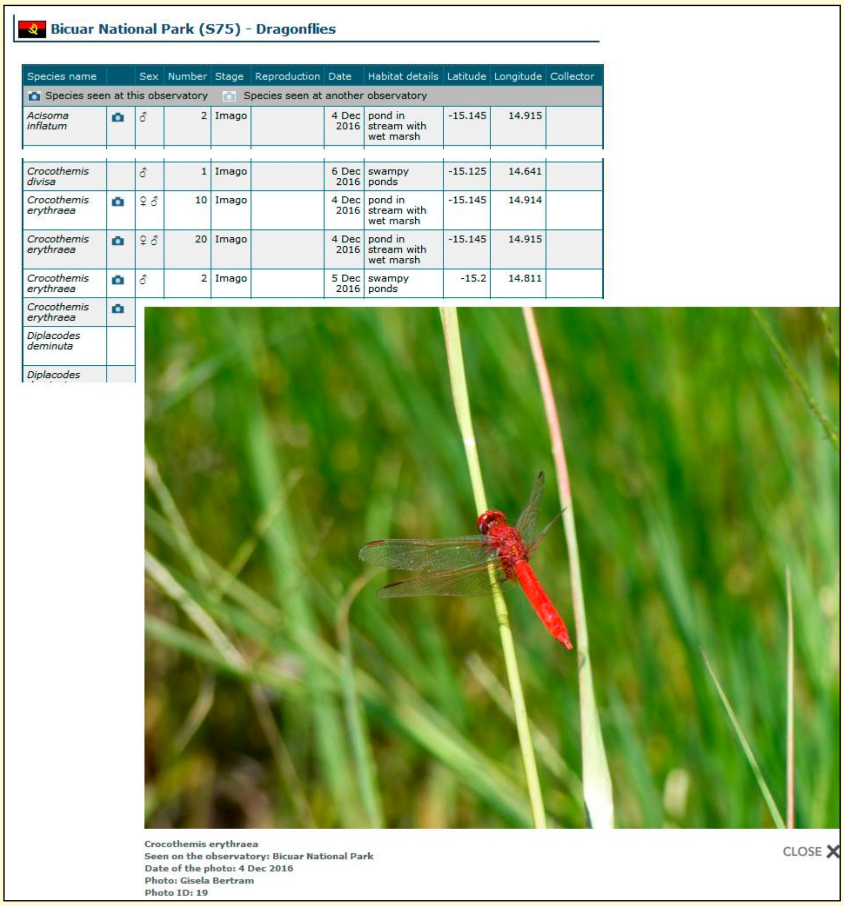

Figure 2: Dragonflies of the Biodiversity Observatory, Bicuar National Park.

Figure 3: Weather and climate information of the Biodiversity Observatory, Bicuar National Park.

Biodiversity

Vegetation dynamics in the Namaqualand Hardeveld — observations from 17 years of annual monitoring

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Abstract: Rangelands in arid areas of southern Africa are prone to degradation through overutilization. Once degraded, rangelands recover very slowly or may not recover without external drivers such as very high-rainfall years. To what extent, at what pace, and to which state Succulent Karoo vegetation is able to recover from long-term exposure to high grazing pressure — from extensive commercial farming, for instance — is poorly understood. We analysed 17 years of annual vegetation monitoring data from the Hardeveld bioregion of the South African Namaqualand. The recording commenced one year after the grazing pressure on the rangeland had been reduced from as much as 120% to 30% of the recommended stocking rate. Non-metric multidimensional scaling (NMDS) of all 17 annual relevés for the 20 plots showed a strong division of the species composition into 8 upland and 12 lowland plots. When applying NMDS to the relevés for the plots separately, in comparison with the lowland plots, upland plots showed a stronger directional change where the species composition shifted away from the initial state. The year-to-year species turnover per habitat, however, was greater on lowland compared to upland habitats. The visualisation of the cover changes per life form type showed that both habitats differed in their life form composition, with a higher dominance of large shrubs in upland compared to lowland habitats. The outcome of the study revealed a habitat-specific response of vegetation to land use change. But even within the habitats, the vegetation showed plot-specific responses of the vegetation to the variances in abiotic factors. We suggest that further analyses should have a stronger focus on species-specific responses at the different sites and employ a more refined life form classification, adapted for the Succulent Karoo vegetation.

Resumo: As pastagens em áreas áridas do Sul de África têm tendência a serem degradadas pela utilização excessiva. Uma vez degradadas, as pastagens recuperam muito lentamente ou podem não recuperar sem factores externos, tais como anos de chuva intensa. Sabe-se pouco sobre até que ponto, a que ritmo e a que estado a vegetação de Succulent Karoo é capaz de recuperar de uma exposição de longa duração a uma alta pressão de pastoreio, por exemplo de agricultura comercial extensiva. Analisámos 17 anos de dados de monitorização anuais de vegetação da bioregião de Hardeveld, da Namaqualand da África do Sul. O registo foi iniciado um ano após a redução da pressão de pastoreio, de 120% para 30% da taxa recomendada de densidade. O escalonamento multidimensional não-métrico (NMDS) de todos os 17 relevés anuais para as 20 parcelas mostrou uma forte divisão da composição específica em oito parcelas de montanha e doze parcelas de planície. Quando o NMDS foi aplicado aos relevés para as parcelas em separado, em comparação com as parcelas de planície, as de montanha mostraram uma mudança direccional mais forte onde a composição de espécies se afastou do estado inicial. Porém, o *turnover* the espécies anual por habitat foi maior em habitats de planície, em comparação com habitats de montanha. A visualização das alterações de cobertura por tipos de formas de vida mostrou que ambos os habitats variaram na sua composição de formas de vida, com uma maior dominância de grandes arbustos nos habitats de montanha, em comparação com os habitats de planície. O resultado do estudo revelou uma resposta da vegetação específica ao habitat em relação à alteração do uso das terras. Mas, mesmo dentro dos habitats, a vegetação mostrou respostas específicas aos plots em relação à variação dos factores abióticos. Sugerimos que futuras análises tenham um foco mais forte nas respostas específicas das espécies nos diferentes locais, e empreguem uma classificação de formas de vida mais refinada, adaptada à vegetação de Succulent Karoo.

Introduction: why do we do long-term monitoring in SASSCAL?

The main land use in southern African drylands is rangeland farming — that is, the use of the natural vegetation as a grazing resource for livestock. The selective grazing behaviour of livestock favours the establishment of unpalatable species. This ultimately leads to a vegetation state that is less suitable for livestock. In the Succulent Karoo biome of southern Africa, selective grazing typically results in sparse vegetation dominated by unpalatable shrubs such as *Galenia africana* (Aizoaceae) and *Pteronia pallens* (Asteraceae), while during the growing season, annuals and geophytes fill in the vegetation gaps (Milton et al., 1994; Milton & Hoffman, 1994; Todd & Hoffman, 1999). Overgrazed rangelands that have reached this degraded vegetation state are less productive and prone to soil erosion, which leads to further degradation of the vegetation. Rangeland ecological concepts that help explain the drivers of vegetation degradation or of recovery are of high scientific and applied relevance.

One of the established concepts in rangeland ecology assumes that the rangeland condition and herbivores are in equilibrium and that vegetation changes are in direct response to herbivore pressure (equilibrium theory of the Clementsian concept). This concept, however, has been questioned for drylands, which exhibit a high variability in rainfall, and the non-equilibrium theory for these rangelands has been put forward (Ellis & Swift, 1988). According to the non-equilibrium theory, rangelands do not necessarily change back to the pre-disturbed state after the livestock pressure has been removed but require abiotic events such as high-rainfall seasons to trigger a vegetation transition to another state (Illius & O'Connor, 1999; Vetter, 2005; von Wehrden et al., 2012). Support for the non-equilibrium theory has been found for the rangelands of the Succulent Karoo (Milton et al., 1994). Results from other studies, however, suggest that biotic factors can well result in a shift in Succulent Karoo vegetation to a less degraded state (Rahlao et al., 2008; van Rooyen et al., 2015). It has therefore been suggested that neither of the two concepts can explain the complex dynamics of arid rangelands exclusively (Gillson & Hoffman, 2007; van Rooyen et al., 2015).

This study will contribute to the understanding of the vegetation dynamics by analysing 17 years of annual permanent plot data from an arid winter rainfall rangeland in southern Africa (Haarmeyer et al., 2010) and focuses on the Namaqualand Hardeveld bioregion within the western Succulent Karoo (Mucina et al., 2006). The undulated landscape of Namaqualand is structured into relatively level lowland habitats and rockier, steeper upland habitats (Desmet, 2007). Lowland habitats, which are more accessible to livestock, tend to be more affected by grazing compared to upland habitats (Riginos & Hoffman, 2003; Anderson & Hoffman, 2007).

The camp studied at Soebatsfontein was used intensively for livestock farming over at least two decades until the year 2000, when the land was handed over to the Soebatsfontein community to be used as communal farmland. With the tenure change, the land use intensity changed from a high to a moderate intensity (Schmiedel et al., 2016). The Soebatsfontein communal farmers who farm in that particular camp take pride in farming sustainably (no overstocking, regular resting periods for the veld, etc.). Our monitoring of the plant communities started in 2001, one year after the land tenure change. By analysing the vegetation change over time, we aim to answer the following research questions:

1. Did the change in land use intensity led to a detectable change in vegetation after 17 years?
2. Is there evidence of a habitat effect in the interannual vegetation variance between upland and lowland habitats of the Soebatsfontein study site?

What did we do and how?

Study site

The study site is located on the farm Kateklip, which forms part of the communal farmland of the Soebatsfontein community (NW corner, –30.1865° to –30.1954° S, 17.54337° to 17.5538° E), at the foothills of the Kamiesberg escarpment in the Northern Cape Province of South Africa. The altitude ranges from 260 m to 435 m above sea level. The climate is characterised by little winter rainfall, with about 130 mm of precipitation per year (Haarmeyer et al., 2010). The mean annual temperature is 17.8 °C, with extremes ranging from a minimum of 3.5 °C in winter to a maximum of 42.4 °C in summer (Haarmeyer et al., 2010). Soils are mainly durisols, cambisols and leptosols derived from a parent material of gneisses (Petersen, 2008). According to Mucina et al. (2006), the area is part of the Namaqualand Heuweltjieveld vegetation unit (SKn 4) within the Hardeveld bioregion of the Succulent Karoo biome. The study site is dominated by succulent dwarf shrubs, mostly from the families Aizoaceae and Crassulaceae (Luther-Mosebach et al., 2012). Mass flowering of annuals (mainly Asteraceae) occurs following the winter rainfall season.

The typical land use at the study site is small-stock farming with sheep and goats. Until 1999 the farmland was owned and managed by the South African diamond mining company De Beers and used for livestock farming. During at least the last two decades of that period, the land was used intensively and stocking rates reached between 80% and 120% of the recommended stocking rate of 9 ha/SSU (Schmiedel et al., 2016). In the year 2000, the farmland was handed over to the about 300 people of the Soebatsfontein community and has since been managed as communal rangeland (Schmiedel et al., 2010). Owing to financial constraints and a conservative farming approach by the responsible farmers, the stocking rate in that particular camp since 2000 has remained below 30% of the recommended stocking rate (Schmiedel et al., 2016).

Study design and data collection

The sampling methodology follows the standardised Biodiversity Observatory design (Jürgens et al., 2012) for long-term biodiversity monitoring. The permanently marked Biodiversity Observatory Soebatsfontein S22 (www.SASSCALObservationNet.org; Hillmann et al., 2018) is

1 km² in size and subdivided into a grid of 100 one-hectare plots. Twenty of the hectare plots were randomly selected using habitat stratification to ensure that all habitat types that occur in the observatory are included in the selection. In the centre of each selected hectare, a 10 m x 10 m plot was permanently marked. For these 20 plots, annual surveys (called *relevés* throughout the text) were conducted from 2001 to 2017 in July or August, which is the main growing season. In each relevé an estimation of the cover (0.01% to 100%) for each vascular plant species was made. Altitude, steepness of slope, and percentage of rock cover per plot were assessed once to describe the habitat characteristics of the plots. Weather data were recorded by the automatic weather station adjacent to Observatory S22 (–30.18294 S, 17.55062 E; see also 'Soebatsfontein' at www.SASSCALweathernet.org; Hillmann et al., 2018).

Data analyses

To identify high- and low-rainfall years, we visualised the interannual variance in the rainfall patterns by plotting the total annual rainfall over the study period in relation to the mean annual rainfall based on the 17 years of recording. We were interested in the general pattern of the species composition to distinguish major habitat types. For that purpose, we visualised the underlying vegetation pattern in the 20 plots by employing an ordination based on non-metric multidimensional scaling (NMDS). The ordination situates the relevés per plot for each of the 17 survey years into a multidimensional space based on their dissimilarity in terms of species composition. The measure of dissimilarity used was the Bray-Curtis distance measure. The more similar the species composition was, the closer the plots were arranged together. We fitted the environmental variables of altitude, slope, and rock cover into the ordination. The fitted environmental variables were correlated with the vegetation ordination at a significance level of $p < 0.05$. The observed divide of the vegetation data into the two main groups (i.e., upland and lowland habitats) enabled us to split the dataset accordingly and analyse the habitat-specific changes in the vegetation.

The species richness in the observatory (350 species per km²) was too high to analyse the vegetation changes at a species level. To reduce the complexity of the dataset, we grouped the species into major strategy types, so-called plant life forms (Raunkiaer, 1937). Plant life forms are defined based on their strategies to survive periods of adverse environmental conditions — in this case, the dry summer season in the Succulent Karoo. Annual plants (or 'therophytes'), for instance, complete their lifecycles within one growing season and survive the dry period as seeds. Bulbous plants (or 'geophytes') completely withdraw during the dry period into the bulb or tuber. Perennial forbs or perennial grasses ('hemicryptophytes') reduce the above-ground biomass to a clump of culms or a rosette of leaves and regrow from buds near the soil surface. The architectures of the dwarf shrubs ('chamaephytes') and tall shrubs and trees ('phanerophytes') remain largely unchanged over the dry period; some of them shed their leaves or even branches, but they continue growing from their remaining branches during the next growing season. These plant life forms have different abilities to respond to environmental variances. Therophytes and geophytes respond strongly to rainfall and thus produce a lot of clutter in the dataset that does not necessarily explain a general trend. We therefore excluded all therophyte and geophyte species from the subsequent analyses. As a result, our analyses focused on perennial life form types such as chamaephytes, phanerophytes, and hemicryptophytes that are visible throughout their entire life span and, if they die, need several years to grow back to a mature stage.

We were interested in changes in the perennial species composition of the vegetation over the study period. Since the species composition varied strongly among the plots, we calculated separate NMDS ordinations for the 17 relevés for each of the 20 plots, again using the Bray-Curtis distance measure for the dissimilarity. To visualise the changes in the species composition from year to year, the relevés were connected by a vector chronologically.

To determine the rate at which perennial species in lowland and upland habitats appeared or disappeared from year to year, we calculated their turnover rate. Finally, we analysed the change in the composition of perennial life forms per habitat type by employing rank clocks, where the interannual changes in vegetation cover per life form were displayed clockwise. We used the following life form types: H = hemicryptophytes, Cmac = macro-chamaephytes (30–50 cm height), Cmes = meso-chamaephytes (15–30 cm), Cmic = micro-chamaephytes (5–15 cm), Cnan = nano-chamaephytes (0–5 cm), Pnan = nano-phanerophytes (50–100 cm).

Results

The interannual variation of the annual rainfall varied between 50% (in the years 2015 and 2017) and 150% (2006, 2011, 2013, and 2016) of the mean annual rainfall of 130 mm (Fig. 1). The mean species richness per plot for a given year varied between < 20 (in 2017) and 40 species (in 2015). Species richness was not closely linked to total annual rainfall. Some years of low annual rainfall had high species numbers (e.g., 2015), and years with high annual rainfall had low species numbers (e.g., 2011) per plot.

The NMDS ordination grouped the 20 plots comprising 17 annual relevés each into two main groups arranged along the NMDS1 axis (Fig. 2). The smaller group to the left-hand side of the ordination was positively associated with the environmental variables altitude, slope, and rock cover and comprised the relevés of the eight upland plots. The other group comprised 12 lowland plots. In both habitat types the relevés per plot were clustered together in ordination space (Fig. 2). For the upland plots the relevés per plot were closely adjacent and overlapped only marginally, whereas the relevés per plot of the lowland were partly overlapping broadly.

Long-term shifts in species composition per plot were investigated by removing the opportunistic annuals and geophytes, which respond to the amount of seasonal rainfall rather than to long-term changes. Since the overall ordination (Fig. 2) showed that the vegetation

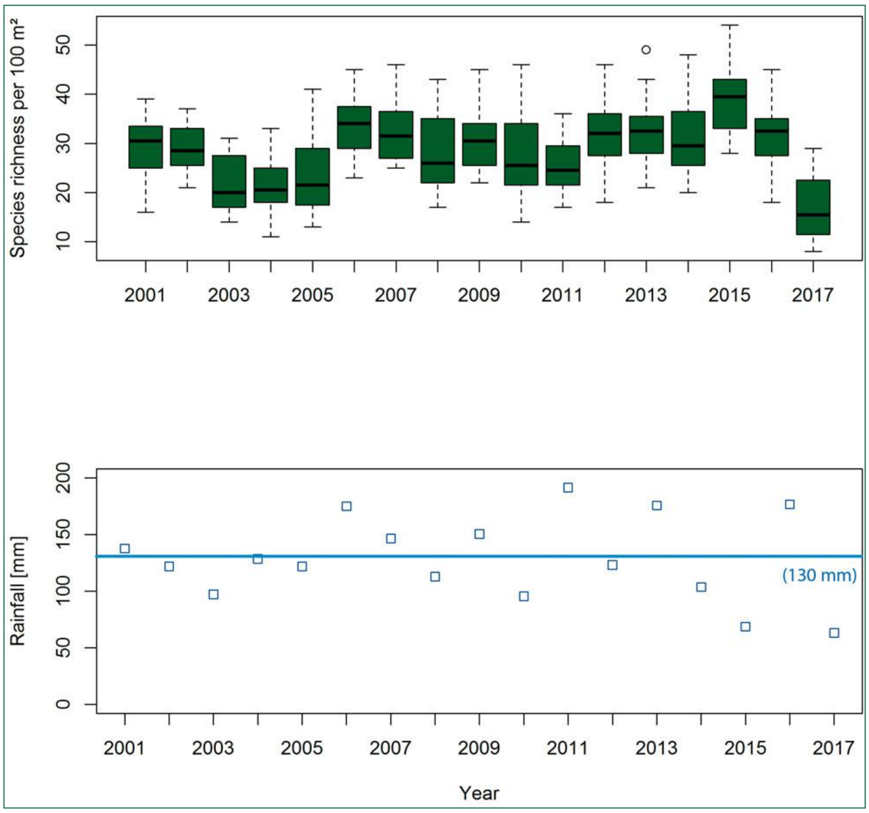

Figure 1: Above: Box plots showing the species richness of the twenty 100 m² plots per year. Bold black line: mean value; green box = 50% variance; hinges = highest and lowest quartile; dot = outlier. Below: Total annual rainfall for the 17-year study period at Soebatsfontein. Horizontal line indicates mean annual rainfall at 130 mm.

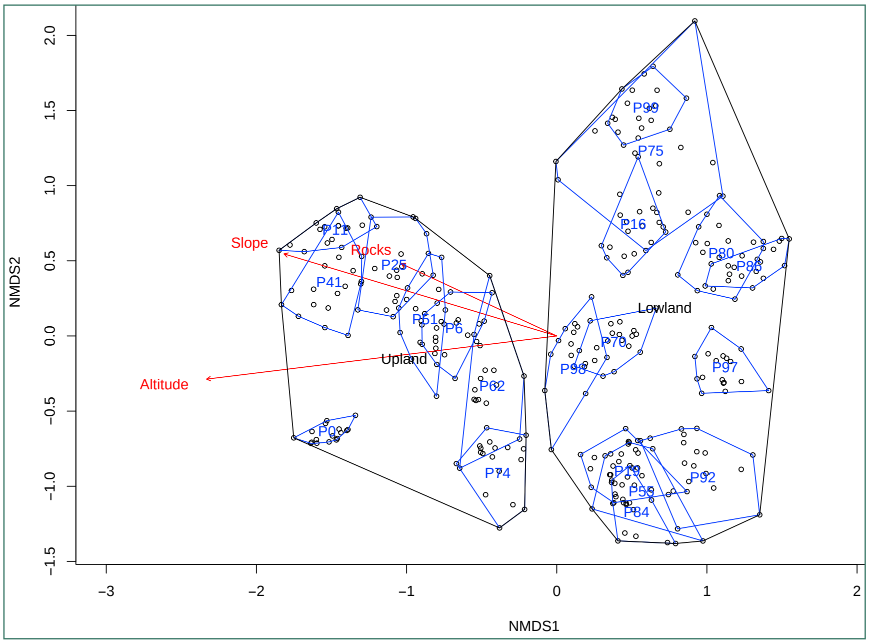

Figure 2: Non-metric multidimensional scaling (NMDS) ordination of 17 relevés of the 20 plots based on all species and three environmental variables, with a significant explanation for the dissimilarity in the species dataset ($p < 0.05$). Slope = slope in %; Altitude = meters above sea level; Rocks = total cover of rocks > 60 cm in diameter. Groups of lowland and upland plots are indicated by black hulls. Relevés belonging to the same plot were surrounded by blue hulls. Measure for dissimilarity was calculated using the Bray-Curtis distance measure.

of most of the plots was quite distinct, we analysed the vegetation changes for each plot separately by employing NMDS ordinations. The position of a relevé in the NMDS ordination space in relation to the other relevés indicates their dissimilarity in species composition. The relevés were connected by a vector following their chronological sequence; the first year of the time series, 2001, was marked with a triangle, and the last year, 2017, was marked with an arrowhead. In this way, the direction of change of the vegetation between relevés for each plot from year to year was visualised. Beyond their interannual oscillations, the movement of the plots showed different patterns (Fig. 3 and 4). Some of the plots showed a directional shift to the right (red arrows), others moved in a semicircle (green arrows), and still others showed change of ambiguous direction (dark red arrows) or even a full circle (blue arrows). Of the 8 upland plots, 5 plots showed a directional change, 2 plots a semicircle, and 1 a full circle whereas among the 12 lowland plots the majority (9 plots) moved either in a semicircle (6 plots) or without a clear direction (3 plots) and only 2 plots showed a directional change.

The interannual appearance, disappearance, and total turnover rates for perennial species on lowland habitats varied more than on upland habitats. The appearance rates on lowland plots ranged from 2% to 17% compared to only 4% to 12% at the upland plots, and the disappearance rates ranged from 3% to 16% on lowland plots compared to 3% to 9% on upland plots (Fig. 5). The total species turnover rate ranged between 8% and 27% at the lowland plots compared to 11% and 21% at the upland plots. The peaks for appearance and disappearance were not synchronised between the habitat types, and the highest peaks of the appearance rate were not related to above-average annual rainfall but seemed to respond with a lag phase of one year.

Lowland and upland habitats differed not only in their species turnover rate but also in their life form composition (Fig. 6). Upland habitats were dominated by nano-phanerophytes and meso-chamaephytes, whereas nano-chamaephytes and hemicryptophytes appeared at much lower rates than in the lowland habitats. The interannual variance between the perennial life forms in the two habitat types also differed. In the upland habitats, the less dominant life forms tended to oscillate more strongly between

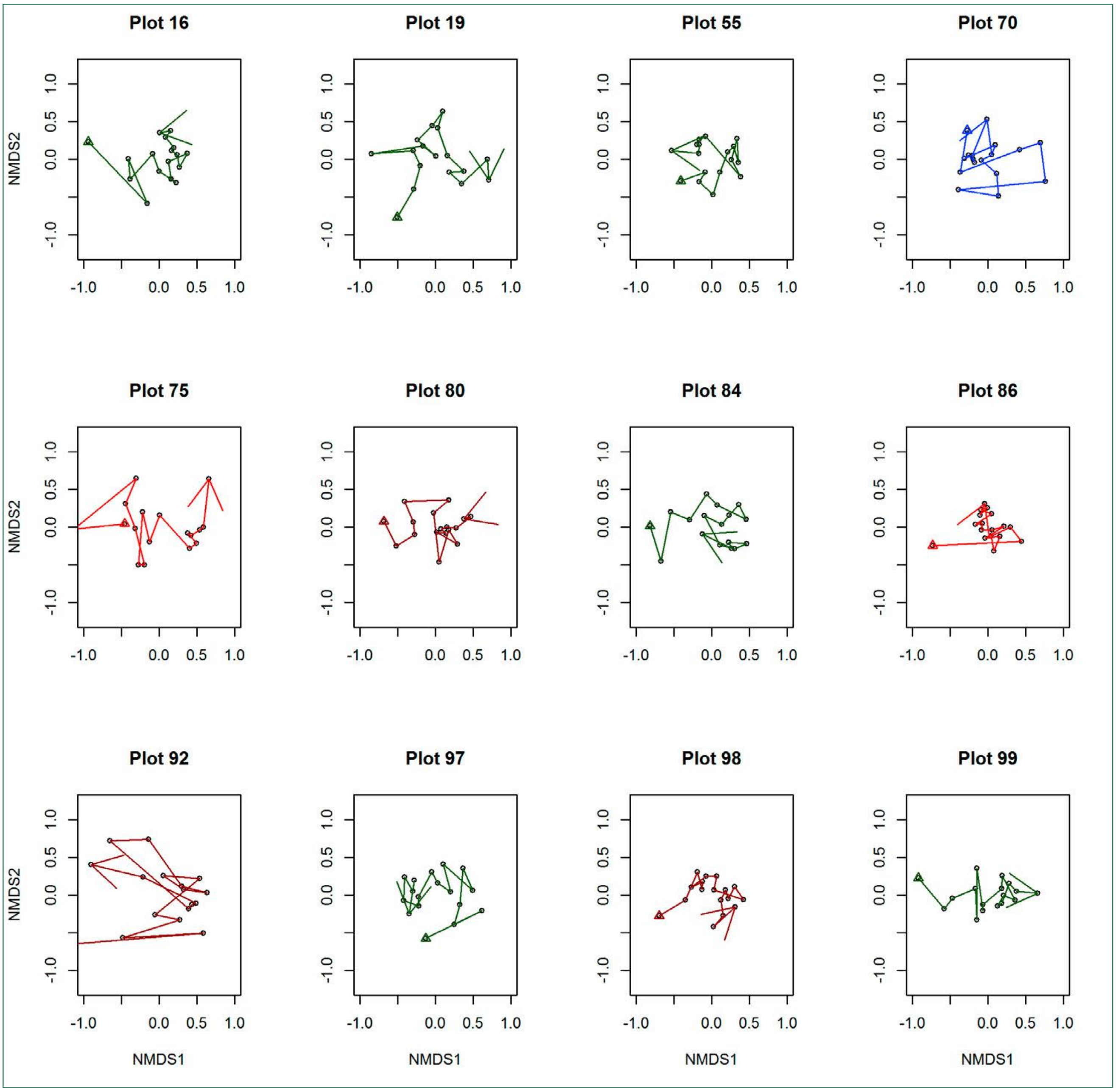

Figure 3: Non-metric multidimensional scaling (NMDS) ordination of the twelve lowland plots based on perennial species composition. A vector connects the relevés of subsequent years. The vectors are colour coded according to the direction of species compositional change. Red = directional change; dark red = change of ambiguous direction; green = semi-circular change; blue = circular change.

the years than in lowland habitats, where only the hemicryptophytes oscillated to a similar extent. In both habitats, life forms that oscillated strongly over the years in response to the seasonal rainfall ended at a lower cover rate in the drought year of 2017 than their starting position in 2001.

Discussion

Despite the wealth of in-depth studies, some of the research results regarding the processes that drive the vegetation dynamics in the arid rangelands are still ambiguous. Some long-term studies from the Succulent Karoo identified directional vegetation change that seemed to have followed biotic factors (Rahlao et al., 2008; van Rooyen et al., 2015). Other studies that analysed vegetation time series data from the arid summer rainfall region of South Africa and covered a period of 47 years (Masubelele et al., 2014) or 23 years (O'Connor & Roux, 1995) found that community change was driven primarily by external, abiotic factors such as rainfall variation.

Our study aimed to contribute another piece to the arid rangeland puzzle by analysing the vegetation dynamics of a rangeland in the Succulent Karoo over 17 years. Since the grazing intensity changed from high to low intensity at the time we commenced the monitoring activity, the generated time series vegetation data also describes the response of the vegetation to the release from heavy grazing pressure. We were therefore interested in how the vegetation responded and whether responses differed between upland and lowland habitats.

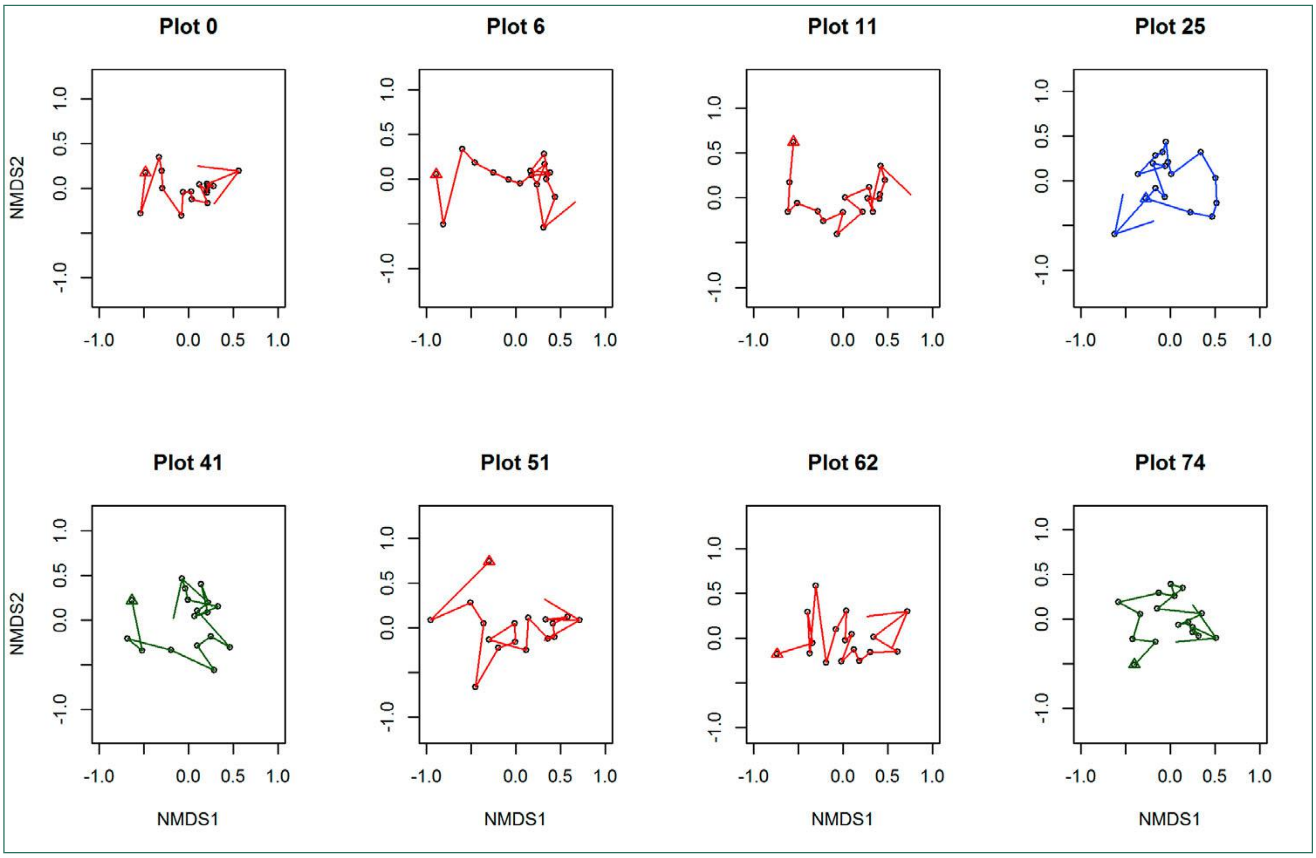

Figure 4: Non-metric multidimensional scaling (NMDS) ordination for the eight upland plots based on perennial species composition. Vectors connect relevés of subsequent years. The vectors are colour coded according to the direction of change in species composition. Red = directional change; green = semi-circular change; blue = circular change.

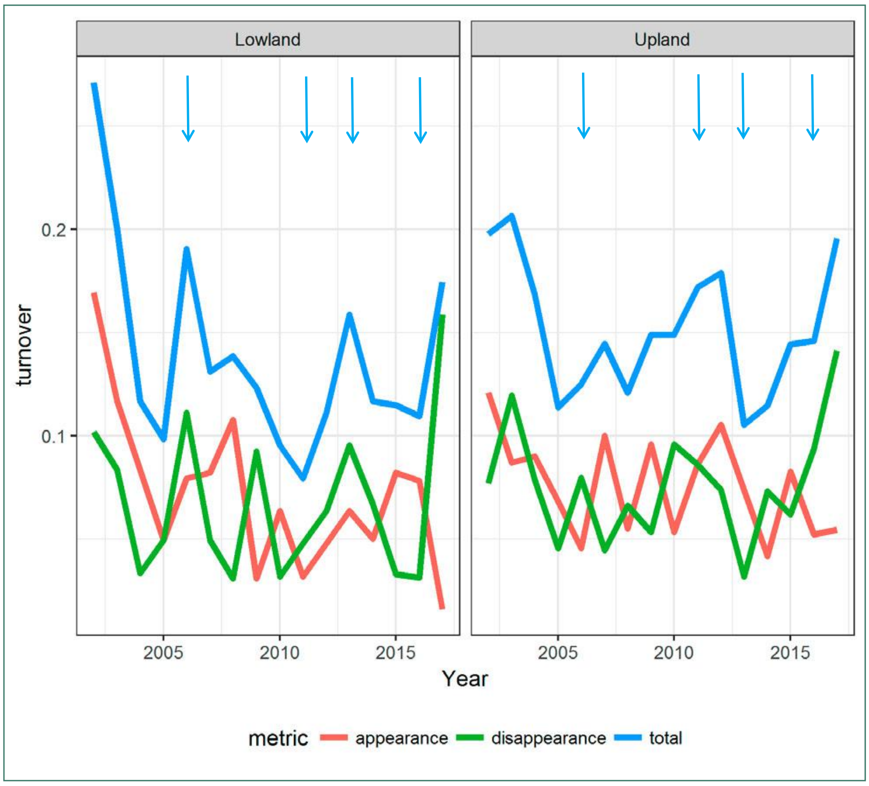

Figure 5: Species turnover based on the appearance and disappearance of perennial species per habitat type (lowland vs. upland) for the years 2001 to 2017. Red = appearance; green = disappearance; blue = total turnover (disappearance + appearance). Blue arrows indicate years with rainfall at 125% above the long-term average of 130 mm (see Fig. 1).

An overall ordination of the 17 relevés all the plots revealed a clear division of the vegetation resulting in 8 upland and 12 lowland plots based on the distinctly different species composition between the two habitat types. Also, the composition of perennial life forms differed, with a higher proportion of larger life forms in the uplands. The higher proportion of large shrubs at the upland habitats can be related to higher soil moisture in the run-on areas beneath the larger rocks and rock faces (Anderson et al., 2010). Upland habitats are also less accessible to livestock than the lowland habitats and are thus exposed to a lower grazing pressure for most of the year (Riginos & Hoffman, 2003; Petersen et al., 2004; Anderson & Hoffman, 2007). Vegetation studies from the Kamiesberg bioregion of Namaqualand, about 50 km inland from our study site, have showed that higher grazing pressure over several decades in the more homogenous lowlands can lead to sparser perennial vegetation cover and a higher proportion of opportunistic species such as therophytes and geophytes as well as opportunistic chamaephytes with a shorter life span (Todd & Hoffman, 1999; Anderson & Hoffman, 2007). These opportunistic species can reach high cover values within a few good rainfall years but die back in a drought year. A higher proportion of opportunistic species among the perennials in the lowlands of our study explains the observed higher interannual fluctuation of appearing and disappearing species and of the total species turnover in lowlands compared to the uplands. The appearance and disappearance of species in a given plot depends on the seasonal rainfall. The fact that the appearances peaked with a time lag of one year are a result of seeds that germinate early in the growing season and are recorded as newly established individuals during the subsequent year after they have survived the dry summer.

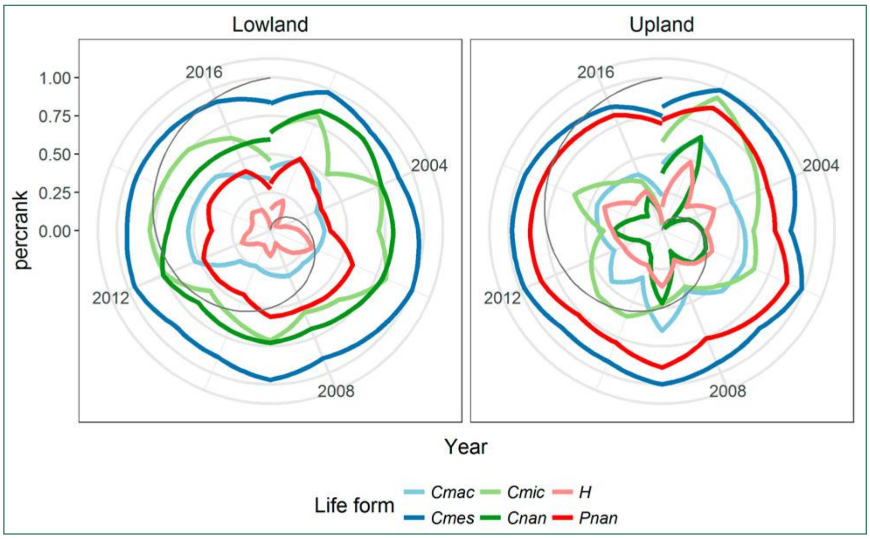

Figure 6: Cover rank clocks per habitat type (upland vs. lowland) for the vegetation classified into eight life-form types at Soebatsfontein: Cmac = macro-chamaephytes (30–50 cm height); Cmes = meso-chamaephytes (15–30 cm); Cmic = micro-chamaephytes (5–15 cm); Cnan = nano-chamaephytes (0–5 cm); H = hemicryptophytes; Pnan = nano-phanerophytes (50–100 cm).

We found that some life form types (e.g., Cnan and Cmac) responded to different extents to interannual rainfall variance in the two habitat types, suggesting that none of the life form types as defined here are generally more resilient to drought than others. Rather, the habitat-specific responses of the life forms result from the fact that the species that are dominant within a life form type differ between the two habitats and that species vary in ecological traits additional to those described by the life form type. Future analyses need to further refine the plant traits used, taking aspects such as life span and level of xeromorphy of the leaves as a general investment strategy to protect water against transpiration into consideration. The importance of a narrower differentiation of life form types has already been suggested by previous studies (Goldberg & Turner, 1986; Hoffman et al., 2009).

Lowland habitats had a higher species turnover rate than uplands, but this generally did not result in a directional change in vegetation. The single-plot ordinations for the lowland plots in most cases showed either circular or little change in the species composition over the 17 years. On the contrary, the relevés of most of the eight upland plots showed trajectories that can be interpreted as directional changes. These directional changes indicate that the upland habitats, which have been less impacted by grazing in the past, responded more quickly to the release of grazing pressure. Also the higher soil moisture content in the upland habitats (Anderson et al., 2010) may have facilitated a more rapid vegetation recovery. Lowland habitats that were more heavily impacted in the past reached a state that could not be changed without external interventions such as sowing or planting palatable species or introducing organic material into the degraded system (Milton et al., 1994; Simons & Allsopp, 2007). Only continuous monitoring will be able to show whether upland plots continue moving into one direction or merely describe larger circular patterns.

Beyond the general differences between upland and lowland habitats, the single plot ordinations also showed that each plot responded individually to the interannual variation in weather conditions. These differences can partly be explained by the high variance in species composition between the plots and by the species-specific responses to the interannual climatic variances and land use change. Also, the small-scale differences in soil features, which are typical for the Succulent Karoo (Petersen et al., 2010), and their effects on the water availability (Francis et al., 2007) add to the complexity of vegetation responses.

The few studies that continuously monitored the vegetation of South African drylands over a period long enough to disentangle the relative influences of climate and herbivory in these arid systems also revealed the complexity of the vegetation dynamics (O'Connor & Roux, 1995; Jürgens *et al.*, 1999; Kraaij & Milton, 2006; Schmiedel *et al.*, 2012; van Rooyen *et al.*, 2015; Vorster, 2017). All authors stress the importance of continuous long-term monitoring to obtain insight into the processes and their drivers. Additionally, O'Connor & Roux (1995), who analysed a vegetation time series of 23 years in the summer rainfall Karoo recorded at four-year intervals, concluded that if monitoring aims to detangle the contribution of internally driven and externally triggered recovery of rangelands, the monitoring interval needs to reflect the pace at which the vegetation of the study system changes, which in their case would have been annually. Also, our data suggest that an annual monitoring interval is critical to understand the vegetation dynamics. In our data, the heterogeneity in the direction and extent of change among the plots over the years would not have been detected if the monitoring had been conducted at longer intervals.

Acknowledgements

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References

Anderson, P.M.L. & Hoffman, M.T. (2007) The impacts of sustained heavy grazing on plant diversity and composition in lowland and upland habitats across the Kamiesberg mountain range in the Succulent Karoo, South Africa. *Journal of Arid Environments*, **70**, 686–700.

Anderson, P.M.L., Hoffman, M.T. & O'Farrell, P.J. (2010) Above ground perennial plant biomass across an altitudinal and land-use gradient in Namaqualand, South Africa. *South African Journal of Botany*, **76**, 471–481.

Desmet, P.G. (2007) Namaqualand - A brief overview of the physical and floristic environment. *Journal of Arid Environments*, **70**, 570–587.

Ellis, J.E. & Swift, D.M. (1988) Stability of African pastoral ecosystems: alternate paradigms and implications for development. *Rangeland Ecology & Management/Journal of Range Management Archives*, **41**, 450–459.

Francis, M.L., Fey, M.V., Prinsloo, H.P., Ellis, F., Mills, A.J. & Medinski, T.V. (2007) Soils of Namaqualand: compensations for aridity. *Journal of Arid Environments*, **70**, 588–603.

Gillson, L. & Hoffman, M.T. (2007) ECOLOGY: rangeland ecology in a changing world. *Science*, **315**, 53–54.

Goldberg, D.E. & Turner, R.M. (1986) Vegetation change and plant demography in permanent plots in the Sonoran Desert. *Ecology*, **67**, 695–712.

Haarmeyer, D.H., Luther-Mosebach, J., Dengler, J. et al. (2010) The BIOTA Observatories. *Biodiversity in southern Africa. Volume 1: Patterns at local scale — the BIOTA Observatories* (ed. by N. Jürgens, D.H. Haarmeyer, J. Luther-Mosebach, J. Dengler, M. Finckh, & U. Schmiedel), pp. 6–801. Klaus Hess Publishers, Göttingen & Windhoek.

Hillmann, T., Muche, G., Josenhans, K. & Jürgens, N. (2018) Online presentation of the SASSCAL ObservationNet. This volume.

Hoffman, M.T., Carrick, P.J., Gillson, L. & West, A.G. (2009) Drought, climate change and vegetation response in the Succulent Karoo, South Africa. *South African Journal of Science*, **105**, 54–60.

Illius, A.W. & O'Connor, T.G. (1999) On the relevance of nonequilibrium concepts to arid and semiarid grazing systems. *Ecological Applications*, **9**, 798–813.

Jürgens, N., Gotzmann, I.H. & Cowling, R.M. (1999) Remarkable medium-term dynamics of leaf succulent *Mesembryanthemaceae* shrubs in the winter-rainfall desert of northwestern Namaqualand, South Africa. *Plant Ecology*, **142**, 87–96.

Jürgens, N., Schmiedel, U., Haarmeyer, D. et al. (2012) The BIOTA Biodiversity Observatories in Africa — a standardized framework for large-scale environmental monitoring. *Environmental Monitoring and Assessment*, **184**, 655–678.

Kraaij, T. & Milton, S.J. (2006) Vegetation changes (1995–2004) in semi-arid Karoo shrubland, South Africa: effects of rainfall, wild herbivores and change in land use. *Journal of Arid Environments*, **64**, 174–192.

Luther-Mosebach, J., Dengler, J., Schmiedel, U., Roewer, I.U., Labitzky, T. & Groengroeft, A. (2012) A first formal classification of the Hardeveld vegetation in Namaqualand, South Africa. *Applied Vegetation Science*, **15**, 401–431.

Masubelele, M.L., Hoffman, M., Bond, W. & Gambiza, J. (2014) A 50-year study shows grass cover has increased in shrublands of semi-arid South Africa. *Journal of Arid Environments*, **104**, 43–51.

Milton, S.J., Dean, W.R.J., du Plessis, M.A. & Siegfried, W.R. (1994) A conceptual model of arid rangeland degradation. *BioScience*, **44**, 70–76.

Milton, S.J. & Hoffman, M.T. (1994) The application of state-and-transition models to rangeland research and management in arid succulent and semi-arid grassy Karoo, South Africa. *African Journal of Range and Forage Science*, **11**, 18–26.

Mucina, L., Jürgens, N., Le Roux, A., Rutherford, M.C., Schmiedel, U., Esler, K.J., Powrie, L.W., Desmet, P.G. & Milton, S.J. (2006) Succulent Karoo biome. *The vegetation of South Africa, Lesotho and Swaziland* (ed. by L. Mucina and M.C. Rutherford), pp. 221–229. South African National Biodiversity Institute, Pretoria.

O'Connor, T.G. & Roux, P.W. (1995) Vegetation changes (1947–1971) in a semi-arid, grassy dwarf shrubland in the Karoo, South Africa: influence of rainfall variability and grazing by sheep. *Journal of Applied Ecology*, **29**, 247–260.

Petersen, A. (2008) *Pedodiversity of southern African drylands*. University of Hamburg, Hamburg.

Petersen, A., Groengroeft, A., Mills, A. & Miehlich, G. (2010) Soils along the BIOTA transects. *Biodiversity in southern Africa. Volume 2: Patterns and processes at regional scale* (ed. by U. Schmiedel and N. Jürgens), pp. 84–92. Klaus Hess Publishers, Göttingen & Windhoek.

Petersen, A., Young, E.M., Hoffman, M.T. & Musil, C.F. (2004) The impact of livestock grazing on landscape biophysical attributes in privately and communally managed rangelands in Namaqualand. *South African Journal of Botany*, **70**, 777–783.

Rahlao, S.J., Hoffman, M.T., Todd, S.W. & McGrath, K. (2008) Long-term vegetation change in the Succulent Karoo, South Africa following 67 years of rest from grazing. *Journal of Arid Environments*, **72**, 808–819.

Raunkiaer, C. (1937) *Plant life forms*. The Clarendon Press, Oxford.

Riginos, C. & Hoffman, M.T. (2003) Changes in population biology of two succulent shrubs along a grazing gradient. *Journal of Applied Ecology*, **40**, 615–625.

Schmiedel, U., Dengler, J. & Etzold, S. (2012) Vegetation dynamics of endemic-rich quartz fields in the Succulent Karoo, South Africa, in response to recent climatic trends. *Journal of Vegetation Science*, **23**, 292–303.

Schmiedel, U., Linke, T., Christiaan, R.A. et al. (2010) Environmental and socio-economic patterns and processes in the Succulent Karoo frame conditions for the management of this biodiversity hotspot. *Biodiversity in southern Africa. Volume 3: Implications for landuse and management* (ed. by M.T. Hoffman, U. Schmiedel, and N. Jürgens), pp. 109–150. Klaus Hess Publishers, Göttingen & Windhoek.

Schmiedel, U., Röwer, I.U., Luther-Mosebach, J., Dengler, J., Oldeland, J. & Gröngröft, A. (2016) Effect of grazing on vegetation and soil of the heuweltjieveld in the Succulent Karoo, South Africa. *Acta Oecologica*, **77**, 27–36.

Simons, L. & Allsopp, N. (2007) Rehabilitation of rangelands in Paulshoek, Namaqualand: understanding vegetation change using biophysical manipulations. *Journal of Arid Environments*, **70**, 755–766.

Todd, S.W. & Hoffman, M.T. (1999) A fence-line contrast reveals effects of heavy grazing on plant diversity and community composition in Namaqualand, South Africa. *Plant Ecology*, **142**, 169–178.

van Rooyen, M.W., Le Roux, A., Geldenhuys, C., van Rooyen, N., Broodryk, N.L. & van der Merwe, H. (2015) Long-term vegetation dynamics (40 yr) in the Succulent Karoo, South Africa: effects of rainfall and grazing. *Applied Vegetation Science*, **18**, 311–322.

Vetter, S. (2005) Rangelands at equilibrium and non-equilibrium: recent developments in the debate. *Journal of Arid Environments*, **62**, 321–341.

von Wehrden, H., Hanspach, J., Kaczensky, P., Fischer, J. & Wesche, K. (2012) Global assessment of the non-equilibrium concept in rangelands. *Ecological Applications*, **22**, 393–399.

Vorster, L. (2017) *Current status and impact (2004–2015) of indigenous ungulate herbivory on the vegetation of Sanbona Wildlife Reserve in the Little Karoo*. University of Cape Town, Cape Town.

References [CrossRef]

Anderson, P.M.L. & Hoffman, M.T. (2007) The impacts of sustained heavy grazing on plant diversity and composition in lowland and upland habitats across the Kamiesberg mountain range in the Succulent Karoo, South Africa. *Journal of Arid Environments*, **70**, 686–700. CrossRef

Anderson, P.M.L., Hoffman, M.T. & O'Farrell, P.J. (2010) Above ground perennial plant biomass across an altitudinal and land-use gradient in Namaqualand, South Africa. *South African Journal of Botany*, **76**, 471–481. CrossRef

Desmet, P.G. (2007) Namaqualand - A brief overview of the physical and floristic environment. *Journal of Arid Environments*, **70**, 570–587. CrossRef

Ellis, J.E. & Swift, D.M. (1988) Stability of African pastoral ecosystems: alternate paradigms and implications for development. *Rangeland Ecology & Management/Journal of Range Management Archives*, **41**, 450–459. CrossRef

Francis, M.L., Fey, M.V., Prinsloo, H.P., Ellis, F., Mills, A.J. & Medinski, T.V. (2007) Soils of Namaqualand: compensations for aridity. *Journal of Arid Environments*, **70**, 588–603. CrossRef

Gillson, L. & Hoffman, M.T. (2007) ECOLOGY: rangeland ecology in a changing world. *Science*, **315**, 53–54. CrossRef

Goldberg, D.E. & Turner, R.M. (1986) Vegetation change and plant demography in permanent plots in the Sonoran Desert. *Ecology*, **67**, 695–712. CrossRef

Haarmeyer, D.H., Luther-Mosebach, J., Dengler, J. et al. (2010) The BIOTA Observatories. *Biodiversity in southern Africa. Volume 1: Patterns at local scale — the BIOTA Observatories* (ed. by N. Jürgens, D.H. Haarmeyer, J. Luther-Mosebach, J. Dengler, M. Finckh, & U. Schmiedel), pp. 6–801. Klaus Hess Publishers, Göttingen & Windhoek.

Hillmann, T., Muche, G., Josenhans, K. & Jürgens, N. (2018) Online presentation of the SASSCAL ObservationNet. This Volume. CrossRef

Hoffman, M.T., Carrick, P.J., Gillson, L. & West, A.G. (2009) Drought, climate change and vegetation response in the Succulent Karoo, South Africa. *South African Journal of Science*, **105**, 54–60. CrossRef

Illius, A.W. & O'Connor, T.G. (1999) On the relevance of nonequilibrium concepts to arid and semiarid grazing systems. *Ecological Applications*, **9**, 798–813. CrossRef

Jürgens, N., Gotzmann, I.H. & Cowling, R.M. (1999) Remarkable medium-term dynamics of leaf succulent *Mesembryanthemaceae* shrubs in the winter-rainfall desert of northwestern Namaqualand, South Africa. *Plant Ecology*, **142**, 87–96. CrossRef

Jürgens, N., Schmiedel, U., Haarmeyer, D. et al. (2012) The BIOTA Biodiversity Observatories in Africa — a standardized framework for large-scale environmental monitoring. *Environmental Monitoring and Assessment*, **184**, 655–678. CrossRef

Kraaij, T. & Milton, S.J. (2006) Vegetation changes (1995–2004) in semi-arid Karoo shrubland, South Africa: effects of rainfall, wild herbivores and change in land use. *Journal of Arid Environments*, **64**, 174–192. CrossRef

Luther-Mosebach, J., Dengler, J., Schmiedel, U., Roewer, I.U., Labitzky, T. & Groengroeft, A. (2012) A first formal classification of the Hardeveld vegetation in Namaqualand, South Africa. *Applied Vegetation Science*, **15**, 401–431. CrossRef

Masubelele, M.L., Hoffman, M., Bond, W. & Gambiza, J. (2014) A 50-year study shows grass cover has increased in shrublands of semi-arid South Africa. *Journal of Arid Environments*, **104**, 43–51. CrossRef

Milton, S.J., Dean, W.R.J., du Plessis, M.A. & Siegfried, W.R. (1994) A conceptual model of arid rangeland degradation. *BioScience*, **44**, 70–76. CrossRef

Milton, S.J. & Hoffman, M.T. (1994) The application of state-and-transition models to rangeland research and management in arid succulent and semi-arid grassy Karoo, South Africa. *African Journal of Range and Forage Science*, **11**, 18–26. CrossRef

Mucina, L., Jürgens, N., Le Roux, A., Rutherford, M.C., Schmiedel, U., Esler, K.J., Powrie, L.W., Desmet, P.G. & Milton, S.J. (2006) Succulent Karoo biome. *The vegetation of South Africa, Lesotho and Swaziland* (ed. by L. Mucina and M.C. Rutherford), pp. 221–229. South African National Biodiversity Institute, Pretoria.

O'Connor, T.G. & Roux, P.W. (1995) Vegetation changes (1947–1971) in a semi-arid, grassy dwarf shrubland in the Karoo, South Africa: influence of rainfall variability and grazing by sheep. *Journal of Applied Ecology*, **29**, 247–260. CrossRef

Petersen, A. (2008) *Pedodiversity of southern African drylands*. University of Hamburg, Hamburg.

Petersen, A., Groengroeft, A., Mills, A. & Miehlich, G. (2010) Soils along the BIOTA transects. *Biodiversity in southern Africa. Volume 2: Patterns and processes at regional scale* (ed. by U. Schmiedel and N. Jürgens), pp. 84–92. Klaus Hess Publishers, Göttingen & Windhoek.

Petersen, A., Young, E.M., Hoffman, M.T. & Musil, C.F. (2004) The impact of livestock grazing on landscape biophysical attributes in privately and communally managed rangelands in Namaqualand. *South African Journal of Botany*, **70**, 777–783. CrossRef

Rahlao, S.J., Hoffman, M.T., Todd, S.W. & McGrath, K. (2008) Long-term vegetation change in the Succulent Karoo, South Africa following 67 years of rest from grazing. *Journal of Arid Environments*, **72**, 808–819. CrossRef

Raunkiaer, C. (1937) *Plant life forms*. The Clarendon Press, Oxford.

Riginos, C. & Hoffman, M.T. (2003) Changes in population biology of two succulent shrubs along a grazing gradient. *Journal of Applied Ecology*, **40**, 615–625. CrossRef

Schmiedel, U., Dengler, J. & Etzold, S. (2012) Vegetation dynamics of endemic-rich quartz fields in the Succulent Karoo, South Africa, in response to recent climatic trends. *Journal of Vegetation Science*, **23**, 292–303. CrossRef

Schmiedel, U., Linke, T., Christiaan, R.A. et al. (2010) Environmental and socio-economic patterns and processes in the Succulent Karoo frame conditions for the management of this biodiversity hotspot. *Biodiversity in southern Africa. Volume 3: Implications for landuse and management* (ed. by M.T. Hoffman, U. Schmiedel, and N. Jürgens), pp. 109–150. Klaus Hess Publishers, Göttingen & Windhoek.

Schmiedel, U., Röwer, I.U., Luther-Mosebach, J., Dengler, J., Oldeland, J. & Gröngröft, A. (2016) Effect of grazing on vegetation and soil of the heuweltjieveld in the Succulent Karoo, South Africa. *Acta Oecologica*, **77**, 27–36. CrossRef

Simons, L. & Allsopp, N. (2007) Rehabilitation of rangelands in Paulshoek, Namaqualand: understanding vegetation change using biophysical manipulations. *Journal of Arid Environments*, **70**, 755–766. CrossRef

Todd, S.W. & Hoffman, M.T. (1999) A fence-line contrast reveals effects of heavy grazing on plant diversity and community composition in Namaqualand, South Africa. *Plant Ecology*, **142**, 169–178. CrossRef

van Rooyen, M.W., Le Roux, A., Geldenhuys, C., van Rooyen, N., Broodryk, N.L. & van der Merwe, H. (2015) Long-term vegetation dynamics (40 yr) in the Succulent Karoo, South Africa: effects of rainfall and grazing. *Applied Vegetation Science*, **18**, 311–322. CrossRef

Vetter, S. (2005) Rangelands at equilibrium and non-equilibrium: recent developments in the debate. *Journal of Arid Environments*, **62**, 321–341. CrossRef

von Wehrden, H., Hanspach, J., Kaczensky, P., Fischer, J. & Wesche, K. (2012) Global assessment of the non-equilibrium concept in rangelands. *Ecological Applications*, **22**, 393–399. CrossRef

Vorster, L. (2017) *Current status and impact (2004–2015) of indigenous ungulate herbivory on the vegetation of Sanbona Wildlife Reserve in the Little Karoo*. University of Cape Town, Cape Town.

BIOTABase — a unique software to handle complex biodiversity observation data and environmental data

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While there are a number of software programmes that offer storage and handling of species data of biocoenoses, a software programme dedicated to handling complex observation data recorded within time series has so far been lacking. Within SASSCAL 1.0, the software BIOTABase has now been developed to make a new dimension of data handling and analysis possible.

Which observation data need to be stored for biodiversity monitoring?

There are many very different approaches to monitoring biodiversity (Proença et al., 2017). Therefore, it is unlikely that a single software will be able to address the needs of all. However, perhaps the approaches that use intensive ground base monitoring (Proença et al., 2017) bring about the most complex and diverse data. BIOTABase (Muche et al., 2012) has been developed to satisfy the needs of just such an intense biodiversity observation scheme (i.e., the SASSCAL observation network).

This SASSCAL biodiversity observation network (Jürgens et al., 2018) uses spatially fixed standardized observation sites in real landscapes that encompass many scales (1 km², 1 ha, 10 000 m², 1 000 m², 100 m², 10 m², 1 m²), relates to complex environmental data (including climate and land use), and observes a wide range of different organismic groups (algae, lichens, mosses, ferns, seed plants, animals) at different temporal scales (allowing time steps from daily to annual to many years). Figure 1 summarizes the typical characteristics schematically. All data, of course, shall be referenced within relevant systems (accepted taxonomic names, output data formats for modern analytical and statistic software). This is made possible by a well-thought-out design with multiple structures that can be accessed as *views*. The following views are used:

- ***Plots***: contains all *invariable attributes of the observation* (e.g., georeferences of plot corners, altitude, slope, inclination and other topographical and relief information, geomorphology, landscape).
- ***Relevés***: contains all information recorded *at a single time stamp* at a plot (see above), including not only lists of species recorded with numerical attributes (Fig. 2) but also environmental data.
- ***Species***: contains the *single record of a species* within a relevé, with all relevant attributes such as abundance or cover values or growth form or single morphological and functional traits. Here, referenced lists of accepted species and synonyms are offered to make data entry efficient and correct. Even the fate of a single collected specimen sent to a specific museum collection is stored here. Species are linked to online catalogues of photographs.
- ***Habitats***: contains all *general environmental information*, including geology and soil properties.
- ***Land uses***: contains information on type and intensity of *land use*, stock composition, etc.
- ***Individuals***: contains information generated from *individual-based* monitoring

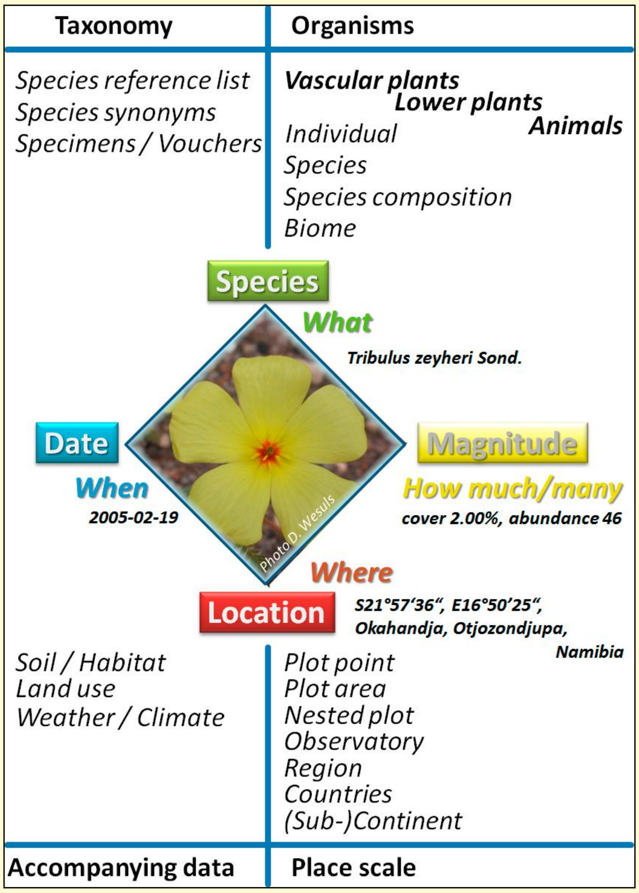

Figure 1: Attributes of a vegetation record.

Which functionalities are needed to explore observation data?

BIOTABase offers all needed tools for modern database management. Datasets can be filtered and selected based on complex combinations of features. Datasets can be split and merged, and there are interfaces allowing import and export to other data formats.

Many functions can be called using customized menus: data entry, data cleansing, lists, and cross-tables as well as interfaces to analytical tools.

Finally, vegetation ecologists can use functions to flexibly design the most diverse data queries and perform analyses directly from BIOTABase or transfer them via interfaces to expert systems. BIOTABase offers output and links to most analytical software currently in use, including Juice (Tichý, 2002), Turboveg (Hennekens & Schaminée, 2001), Google Earth (https://www.google.com/earth), ArcGIS (http://www.arcgis.com), QGIS (https://qgis.org), Saga-GIS (http://www.saga-gis.org), Ordinations and Cluster Programmes via R (https://www.r-project.org), and spreadsheet software such as MS Excel or database software such as MS Access, some of them with specific exchange formats, and others with CSV files or ODBC links.

The BIOTABase software can be downloaded free of charge from the SASSCAL website (http://www.sasscal.org/?page_id=1029) or the BIOTA AFRICA website (http://www.biota-africa/biotabase_ba.php).

References

Hennekens, S.M. & Schaminée, J.H.J. (2001) Turboveg, a comprehensive database management system for vegetation data. *Journal of Vegetation Science*, **12**, 589–591.

Jürgens, N., Strohbach, B., Lages, F., Schmiedel, U., Finckh, M., Sichone, P., Hahn, L.-M. & Zigelski, P. (2018) Biodiversity observation — an overview of the current state and first results of biodiversity monitoring studies. This volume.

Muche, G., Schmiedel, U. & Jürgens, N. (2012) BIOTA Southern Africa Biodiversity Observatories vegetation database. *Vegetation databases for the 21st century* (ed. by Dengler, J., Oldeland, J., Jansen, F., Chytrý, Ewald, J., Finckh, M., Glöckler, F., Lopez-Gonzalez, L., Peet, R.K. & Schaminée, J.H.J.), *Biodiversity & Ecology*, **4**, 111–123.

Proença, V., Martin, L.J., Pereira, H.M. et al. (2017) Global biodiversity monitoring: from data sources to essential biodiversity variables. *Biological Conservation,* **223**, 256–263.

Tichý, L. (2002) Juice, software for vegetation classification. *Journal of Vegetation Science*, **13**, 451–453.

Vascular plant species name	Cover total	Abundance	Coll.-No.
Amellus microglossus	0.10	100	
Atriplex lindleyi ssp. inflata	3.00	20	
Atriplex semibaccata	10.00	1000	
Chenopodium album	8.00	200	
Dimorphotheca sinuata	0.01	1	
Drosanthemum hispidum	1.00	5	
Galenia sarcophylla	0.10	10	
Tribolium utriculosum	1.00	100	
Lycium oxycarpum	0.50	1	
Manochlamys albicans	0.10	1	
Mesembryanthemum guerichianum	5.00	40	
Mesembryanthemum hypertrophicum	30.00	1000	
Foveolina dichotoma	8.00	1000	
Oxalis pes-caprae	0.10	10	
Phyllobolus trichotomus	0.01	1	
Psilocaulon dinteri	3.00	15	
Tetragonia microptera	0.10	10	
Addition of items	70.02	3514	

Lower plant species name	Cover total	Abundance	Coll.-No.
Buellia sipmanii	0.10		
Caloplaca elegantissima	0.10		
Lecidella crystallina	0.10		
Neofuscelia dregeana	0.10		
Xanthomaculina walteri	0.10		
Addition of items	0.50		

Animal species name	Abundance	Coll.-No.
Anoplolepis steingroeveri		190 215
Hodotermes mossambicus		190 214
Ocymyrmex velox		190 216
Psammotermes allocerus		190 213

Figure 2: Relevé elements for vascular plants (example from Soebatsfontein), lower plants (example from Central Namib), and animals (example from the Kunene region).

Biodiversity

The response of small mammal communities to low and high fire recurrences in Kafue National Park, Zambia

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Abstract: To investigate the influence of fire on the communities of small mammals in the Kafue National Park, we trapped 105 individuals (belonging to the families Nesomyids, Murids, Sciurids, and Soricids) in the dry season of 2014 and 2015. We employed 6,273 trap-nights in sites representing three major habitats of small mammals (grassland, miombo woodland, and termitaria) and two fire regimes: namely, high and low fire recurrence. Fire age was assigned based on the last event of fire at a trapping site. These three (vegetation, fire recurrence and age) served as predicator variables, whilst community structure, species richness, and body mass served as response variables. Vegetation had a significant effect on all response variables. Communities in termitaria and grassland overlapped, whilst miombo woodland was set apart. Termitaria was the most species-rich of the habitats and may serve as refugia for species in times of disturbance. In the low and high fire recurrence areas, fire age had different effects on the response variables. In the low fire recurrence areas, species richness increased with time since the last fire occurred, while in the high fire recurrence areas, it decreased accordingly. This could be in response to the reduction in cover available to shelter from predation and other environmental factors, as fire acts to reduce vegetation biomass. This response could also be a function of the animals' life-history traits, particularly of body size, which decreased as time passed since the last fire, implying a higher vulnerability of the smaller-sized species to the current fire regime. Further, fire also had an influence on the dietary resource use of rodents, as they tended to broaden their dietary niches in areas of high fire recurrence compared to low fire recurrence areas. This corroborates the notion that small mammals can cope with either frequent or infrequent burning.

Resumo: Para investigar a influência do fogo nas comunidades de pequenos mamíferos no Parque Nacional de Kafue, capturámos 105 indivíduos (pertencentes às famílias Nesomyids, Murids, Sciurids e Soricids) na época seca de 2014 e de 2015. Aplicámos 6 273 armadilhas em locais que representam três grandes habitats de pequenos mamíferos (prados, bosques de miombo e colónia de térmitas) e dois regimes de fogo, recorrência de fogo alta e recorrência de fogo baixa. A idade do fogo foi atribuída com base no último evento de incêndio num local de armadilhagem. Estas três serviram como variáveis preditivas, enquanto que a estrutura da comunidade, a riqueza específica e a massa corporal serviram como variáveis de resposta. A vegetação teve um efeito significativo em todas as variáveis de resposta. As comunidades em colónias de térmitas e prados sobrepuseram-se, enquanto que os bosques de Miombo ficaram à parte. As colónias de térmitas foram as mais ricas em espécies e poderão servir como refúgio para espécies durante períodos de perturbação. Nas áreas de alta e baixa recorrência de incêndios, a idade do fogo teve diferentes efeitos nas variáveis de resposta. Nas áreas de baixa recorrência, a riqueza específica aumentou com o tempo desde o último incêndio, diminuindo nas áreas de alta recorrência. Isto poderá ser o resultado da redução da cobertura disponível para abrigar da predação e outros factores ambientais, pois o fogo reduz a biomassa da vegetação. Esta resposta pode também ser uma função dos seus traços de história de vida, particularmente o tamanho do corpo, o qual diminiu à medida que o tempo passou desde o último incêndio, implicando uma maior vulnerabilidade das espécies de porte pequeno aos regimes actuais de fogo. Além disso, o fogo teve também uma influência no uso dos recursos dietários pelos roedores, pois estes tenderam a alargar os seus nichos dietários em áreas de alta recorrência de fogos, em comparação com áreas de baixa recorrência. Isto corrobora a noção de que os pequenos mamíferos podem tanto lidar com incêndios frequentes como infrequentes.

Introduction

Small mammals assume various roles in ecosystem functioning. They act upon plant communities due to herbivory and seed predation (Young et al., 2015), as agents of soil aeration and creation through their burrowing activities (Martin, 2003; Kalies & Covington, 2012), pests and pest controllers through their consumption of large amounts of vegetation and invertebrates (Seig, 1987; Timbuka & Kabigumila, 2006), and as food for a variety of predators in ecosystems (Happold, 2013; Happold & Happold, 2013). Yet their importance in ecosystems such as the Kafue National Park (KNP) is often overlooked, as they do not attract as much attention compared to the large charismatic species in the park. Further, they are often considered to be vermin, appearing to benefit from human disturbances in contrast to the large mammals (Young et al., 2015).

Yet as with larger species, many small mammals may also be vulnerable to anthropogenic impacts. Reasons for this vary between sites and small mammal communities (Swihart et al., 1988; Rowe-Rowe, 1995; Bösing et al., 2014; Young et al., 2015; Namukonde et al., 2017). Bush fires represent one such potential anthropogenic disturbance and are a common phenomenon in the KNP, occurring annually (Kelly, 2014). Fire is used by the park's management for a number of purposes, including to: (1) reduce the impact of late dry season fires, (2) improve visibility for photographic tourism, and (3) provide fresh fodder for game (NPWS/JICA, 1999; Kampamba et al., 2005; Chanda, 2007). Since very little is known about the influence of these fires on small mammal species and their community characteristics, we studied the effect of repeated bushfires on their community properties in the Busanga Flood Plain (BFP) of the KNP.

Figure 1: Pitfall lines in (a) grassland and (b) miombo woodland.

Methods

Trapping sites were selected based on vegetation, land use, and fire regime. Vegetation descriptions followed Mwima (2006); land use was set out as prescribed by the management zones of Kafue National Park (NPWS/JICA, 1999; ZAWA, 2013); and fire recurrence was established using remote sensing data compiled by Kelly (2014). In each of the vegetation types (grassland, termitaria, and miombo woodland), replicate trapping sites were set in areas of low and high fire recurrence. Sites that experienced fewer than eight years of fire between the years 2000 and 2013 were classified as low fire recurrence sites and those that experienced eight or more fires during this period were classified as high fire recurrence sites.

For each site, the age of fire was assigned as 'fire age' from 1 to 4 (1=very recent fire occurring few weeks prior to trapping, 2=site burnt during the early fire season, 3=site burnt in the previous year, and 4=site without fire scars or scars from several years ago). This categorisation was based on the researchers' own field observations and was verified by park staff and tour operators in the area. At each of these sites, three transect lines were established, each with 11 pitfall traps (11 x 15-liter buckets), 22 Sherman (22x LFA-TDG 7.5 x 9 x 23 cm) and 8 Tomahawk (four TH 41 x 13 x 13 cm and four TH 48 x 15 x 15 cm sized with one door) live traps baited with peanut butter and oats, following methods outlined by Stanley and Goodman (2011 a, b) and Stanley et al. (2011). Pitfall traps targeted shrews and rodents that were too small to trigger trap doors in the Sherman and Tomahawk traps. The latter two trap types were set with the intention of trapping medium-sized rodents. Trapping was conducted in the dry season of 2014 and 2015, as the BFP is inaccessible during the wet season. All traps were set for three days and nights consecutively and were checked twice per day (morning 06–07 hr and evening 16–17 hr). The

Biodiversity

number of traps set was small, a deliberate decision to enable a standardised trapping approach that could be applied at all sites and conditions. Although the inventories were likely to be incomplete, the standardised trapping efforts at all sites should represent representative sampling that allows robust comparisons between sites and conditions. Figure 1 provides a depiction of the trap lines set in grassland and miombo woodland.

In order to determine the dietary resource use of the small mammals in areas of high and low fire recurrence, we employed stable isotope biochemistry techniques. This technique provided quantitative records of the feeding ecology of each species based on the stable isotopes of nitrogen ($\delta^{15}N$) and carbon ($\delta^{13}C$) found in the rodents' hair tissue. Values of $\delta^{13}C$ reflected the carbon source of the animal's food, whilst $\delta^{15}N$ reflected its trophic positioning in a community (Fry, 2008; Crowley, 2012; Namukonde et al., 2018). Coexisting species avert competition for habitat resources through trophic specialisations (MacArthur & Levins, 1967) and through differences in their body mass and sizes (Hutchinson, 1959), which reflect their niche differences. Niche width reflects the dietary space or length a species inhabits. Here the standard deviation of $\delta^{13}C$ and $\delta^{15}N$ of species that had more than two individuals trapped in low and high fire recurrence area was used to describe the niche widths. Linear models and multivariate analysis were used to assess the effect of vegetation, land use, and fire on the community measures.

Results

During the study period, 105 individuals (recaptures not included) belonging to 16 species (11 rodent and 5 shrew species) of small mammals were captured in 51 transects laid in the 17 trapping sites in termitaria, grassland, and miombo woodland vegetations (Table 1).

Ubiquitous species trapped included *Mastomys natalensis,* whose abundance varied between the three vegetation types. Except for the bush squirrel (*Paraxerus cepapi*), which is arboreal, all the captured species were terrestrial. The bush squirrel was the largest species (189 ±22g) trapped and was found in termitaria and miombo woodland only. The smallest species (3–4 g) captured were *Mus minutoides* (rodent) and *Crocidura fuscomurina* (shrew). These species were trapped mostly in termitaria and in only one transect in grassland. Community structure and composition of the small mammals differed significantly between the three vegetation types (per MANOVA: $F = 3.34$; $p < .01$, Fig. 2). Communities in termitaria and grassland had overlaps whilst miombo woodland was set apart. Termitaria was the most species-rich (3.6 ± 1.1 species/site) habitat, followed by grass-

Table 1: Transect characteristics and small mammal captures in the Busanga Flood Plains in 2014 and 2015. Captures reflect numbers of individuals; recaptures are not considered. Habitat: T = Termitaria, G = Grassland, Mi = Miombo woodland; Fire recurrence: L = low, H = high; Fire age: (1) very recent burn occurring in the mid dry season of the same year of trapping; (2) area burnt during the early fire season in same year of trapping; (3) area with fire scars from the previous year; (4) area without or with very few fire scars from several years ago; Management zone: Iz = intensive utilization by tourism, W = wild zone (rarely used), Wz = wilderness (no access) (Source: Namukonde *et al.* 2017).

Trapping sites	**Vegetation type**	**Fire recurrence**	**Firge age**	**Management zone**	***Mus minutoides***	***Mastomys natalensis***	***Saccostomus campestris***	***Paraxerus cepapi***	***Lemniscoyms rosalia***	***Mus triton***	***Aethomys nyikae***	***Steatomys pratensis***	***Gerbilliscus leucogaster***	***Aethomys chrysophilus***	***Otomys angoniensis***	***Crocidura fuscomurina***	***Suncus lixus***	***Crocidura cyanea***	***Crocidura mariquensis***	***Crocidura hirta***	**Species number**
Iz0H1	T	L	4	Iz	3	3										4					3
Iz7H1	T	H	2	Iz		2	1														2
W7I3	T	L	3	Wz		3				1	1	1									4
Wz0H1	T	H	1	Wz	2	2		3	1							1					5
Wz7H1	T	H	2	W		2	1							1						1	4
Iz0C13	G	L	2	Iz		8					1										2
Iz7C14	G	H	2	Iz		1							19		1						3
W0C10	G	L	4	W		4												2	1	2	4
W7C10	G	H	3	W		2															1
Wz0C13	G	L	3	Wz	1	4										3					3
Wz7C10	G	H	2	Wz		2											1				2
Iz0D7	Mi	L	2	Iz				1					1								2
Iz7D7	Mi	H	3	Iz									3								1
W0D1	Mi	L	2	W									3								1
W7D1	Mi	H	2	W																	0
Wz0D5	Mi	L	1	Wz		1		11													2
Wz7D1	Mi	H	2	Wz																	0
Total					6	34	2	15	1	1	2	1	26	1	1	8	1	2	1	3	105
Proportion relative to the total captured (%)					5.7	32	1.9	14	1	1	1.9	1	25	1	1	7.6	1	1.9	1	2.9	
Body mass (g)					3.6	24	59	189	43	23	98	20	102	30	112	3.1	11	8	12	15	
SD					0.6	5.3	7.1	22			49		37	1.4		0.8	0.4	1.4		2.7	
Trophic guild					O	O	G	O	H	O	O*	G	O	O	H	I	I	I	I	I/C	

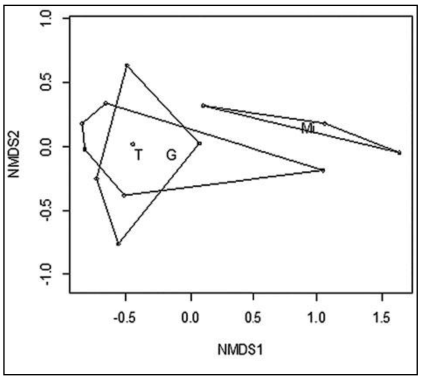

Figure 2: Small mammal communities in different vegetation types (Source: Namukonde et al., 2017).

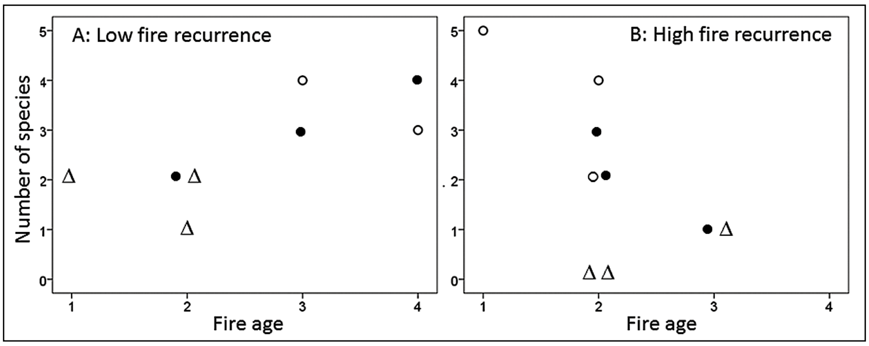

Figure 3: Relationship between fire and small mammal species numbers at sites subject to low fire recurrence (A) and high fire recurrence (B). Categories of “Fire age”: 1: very recent burn from the mid fire season of the same year of trapping; 2: area burnt during the early fire season in same year of trapping; 3: area with fire scars from the previous years’ burning season; 4: area without or very few fire scars from several years ago; ○ = termitaria, ● = grassland, ∆ = miombo.

land (on average 2.5 ±1.0 species/site) and miombo (1.0 ±0.9 species/site). Species richness differed significantly between the three vegetation types (ANOVA: $F_{2, 14}$ = 8.97; p = .003).

As a single factor, fire recurrence had no significant influence on the species richness ($F_{1,15}$ = 7.77*;* p = 0.07) of small mammals; neither was fire age correlated to species richness (Pearson correlation: r = -0.08*;* p = 0 .75*;* n = 17). However, when the two factors were combined, the effect of fire recurrence became significant (while fire age remained non-significant [GLM: fire age: F = 1.02; p = 0 .33; fire recurrence: F = 4.66, p =0.049; model: F = 2.40, p = 0.13]). In the low fire recurrence areas, species richness was positively correlated to fire age, whereas in the high fire recurrence area, the opposite was observed (Fig. 3).

Because species varied between sites, we replaced species identities with life history traits, such as body mass, social systems, activity patterns, diet, habitat utilisation, locomotion, and litter size (Violle et al., 2007; Namukonde et al., in press). For body mass, the evidence pointed to smaller-sized species being most affected by the current fire regime. The average body size decreased with increasing time after a site had experienced fire (Fig. 4).

Regarding dietary resource use, rodent species tended to broaden their dietary niches in areas of high fire recurrence compared to areas of low fire recurrence. This was evident for seven out of eight comparisons (p = .035, Sign test, Fig. 5), with the exception being *Mus minutoides,* which had a smaller standard deviation in $\delta^{13}C$ in areas of high than in areas of low fire recurrence. All of these rodents are omnivores. For shrews (*Crocidura fuscomurina*), the pattern was reversed; shrews are predominately insectivores.

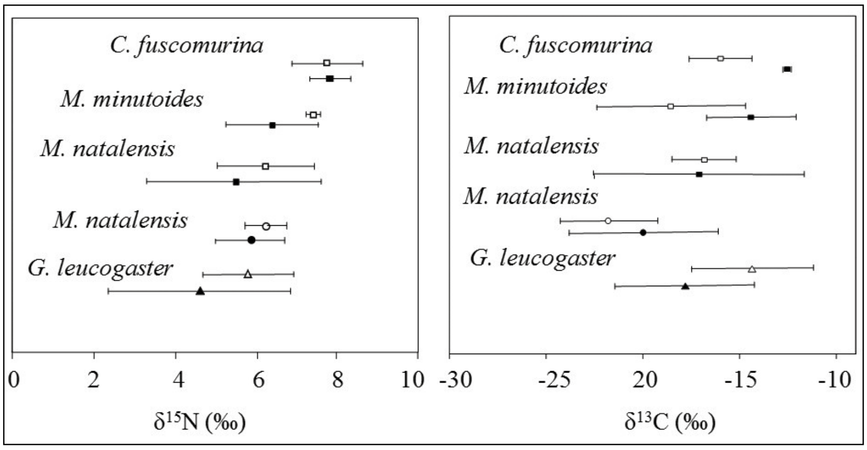

Figure 5: Niche width indicated by $\delta^{15}N$ (A) and $\delta^{13}C$ (B) in high and low fire recurrence areas. ○= grassland, □ = termitaria and ∆ = miombo; open symbols: low fire recurrence, filled symbols: high fire recurrence. Values are means and standard deviation. (Source: Namukonde et al.,2018).

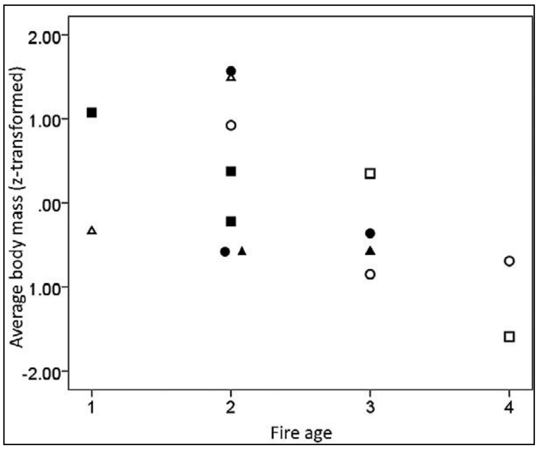

Figure 4: Relationship between fire and mean body mass of small mammal species at sites subjected to low or high fire recurrence. Average body mass of small mammal species was z-transformed per vegetation type. Categories of “Fire age”: 1: very recent burn from the mid fire season of the same year of trapping; 2: area burnt during the early fire season in same year of trapping; 3: area with fire scars from the previous years’ burning season; 4: area without or very few fire scars from several years ago. ○ = grassland, □ = termitaria, ∆ = miombo; open symbols: low fire recurrence, filled symbols: high fire recurrence (Source: Namukonde *et al.,* 2017)

Biodiversity

Discussion

The high species richness of termitaria was thought to be influenced by their ecological function as refugia against disturbance (e.g., flooding and fire) and as sources of recolonisation (Namukonde et al., 2017). Termite mounds are a prominent feature of termitaria and, owing to their structure, they are likely to offer underground shelter to small mammals. They also tend to have more friable soils that are easier to dig as compared to those in the grasslands of flood plains. Moreover, in the wet season and in times of floods, their elevation offers dry ground.

Though most large mammals seem adapt to fires (Green et al., 2015), small mammals are seemingly affected by its effect on cover, particularly its reduction (Swanepoel, 1981; Yarnell et al., 2007, 2008). Land transformation due to high or low recurrent fire frequencies often leads to different responses between small mammal species (Fig. 3 & 4; Rowe-Rowe, 1995; Young et al., 2015: Namukonde et al., 2017). This supports predictions regarding the shift of community composition and structure of small communities in the park based on the evidence pointing to the significant differences in primary productivity between frequently burnt areas and areas that do not experience frequent fires (D. Kuebler, University of Hamburg, unpubl. data). According to Moss (1973) and Chanda (2007), fires occurring in areas of high fire recurrence have the potential to alter the range land into more open areas. Thus, based on the foregoing and considering the lean resources available to manage fires in the park, perhaps emphasis should be placed on important habitats such as termitaria, whose perceived role as refugia for species from disturbance and recolonisation is reaffirmed by the overarching structure of the dietary space assumed by communities of rodents and shrews over those in miombo woodland and grassland (Namukonde et al., 2018).

Fire also affects the dietary resource use of rodents. In areas of high fire recurrence, rodents had broader dietary niches than in areas of low fire recurrence (Fig. 5). This suggests that competition for resources may be relaxed as species do not need to occupy specific and exclusive niches, because fire acts as a temporal and spatial disturbance in the context of stochastic community processes (Begon et al., 2006; Namukonde et al., 2018). This is an important finding, as it provides an understanding of the boundary conditions under which small mammals reach their carrying capacity in this ecosystem. However, there may be other ecological processes working to depress the populations of rodents from reaching their carrying capacities in the high fire recurrence areas. As pointed out previously, habitat conditions (i.e., availability of cover to avert predation and food to sustain populations) may also contribute to depressing the rodent populations in high fire recurrence areas. Needless to say, these processes are also present in low fire recurrence areas.

For shrews (*Crocidura fuscomurina)*, the opposite condition persists as they appear to have narrower dietary niches in areas under high fire recurrence. According to Namukonde et al. (2018), this shrew's niche width is seemingly unaffected by competition, as it is clearly separated from other shrews by body mass following Hutchinson's rule (Hutchinson, 1959). Hutchinson's rule states that species can coexist if they differ in body mass by a factor of two or more, or in linear body size dimensions by a factor of 1.4. This is an important finding, as it, too, provides an understanding of the boundary conditions under which small mammals reach their carrying capacity in this ecosystem.

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References

Begon, M., Harper, J.L., & Townsend, C.R. (2006) *Ecology.* Blackwell, Oxford.

Bösing, M.B., Haarmeyer, D.H., Dengler, J. et al. (2014) Effects of livestock grazing and habitat characteristics on small mammal communities in the Knersvlakte, South Africa. *Journal of Arid Environments*, **104**, 124–131.

Chanda, J. (2007) *Fire management plan for Kafue National Park and its surrounding game management areas*. Zambia Wildlife Authority, Chilanga, Zambia.

Crowley, B.E. (2012) Stable isotope techniques and applications for primatologists. *International Journal of Primatology*, **33**, 673–701.

Fry, B. (2008) *Stable isotope ecology*. Springer-Verlag, New York.

Green, S.D., Roloff, G.J., Heath, B.R., et al. (2015) Temporal dynamics of the response by African mammals to prescribed fire. *Journal of Wildlife Management,* **79**, 235–242. DOI:10.1002/jwmg.827.

Happold, D.C.D. (2013) *Mammals of Africa. Volume III: Rodents, hares, and rabbits*. Bloomsbury, London.

Happold, M. & Happold, D.C.D. (2013) *Mammals of Africa. Volume IV: Hedgehogs, shrews, and bats*. Bloomsbury, London.

Hutchinson, G.E. (1959) Homage to Santa Rosalia, or why are there so many kinds of animals? *American Naturalist,* **93**, 137–159.

Kalies, E.L. & Covington, W.W. (2012) Small mammal community maintains stability through compensatory dynamics after restoration of a ponderosa pine forest. *Ecosphere* **3**, 78. doi:10.1890/ES12-00143.1

Kampamba, G., Chansa, W. & Changwe, K. (2005) *Fire management plan for protected areas in Zambia*. Zambia Wildlife Authority, Chilanga, Zambia.

Kelly, D. (2014) *A map of the Kafue ecosystem: Fire history 2000–2013*. The Nature Conservancy, Lusaka, Zambia.

MacArthur, R.H., & Levins, R. (1967) The limiting similarity, convergence, and divergence of coexisting species. *American Naturalist,* **101**, 377–385.

Martin, G. (2003) The role of small ground-foraging mammals in topsoil health and biodiversity: Implications to management and restoration. *Ecological Management & Restoration*, **4**, 114–119.

Moss, P. (1973) *Notes on the interim fire use and fire control programme for the Kafue National Park*. National Parks and Wildlife Services, Chilanga, Zambia.

Mwima, H. (2006) *Vegetation monitoring manual for the Kafue National Park*. Zambia Wildlife Authority, Mumbwa, Zambia.

Namukonde, N., Kuebler, D. & Ganzhorn, J. U. (2017) Differential effects of fire on small mammal communities in the Busanga Flood Plain, Zambia. *Tropical Conservation Science,* **10**, 1-13. DOI:10.1177/1940082917725439

Namukonde, N., Muleya, Z. & Ganzhorn, J. U. (in press) Small mammals in Kafue National Park, Zambia. *Verhandlungen des Naturwissenschaftlichen Vereins in Hamburg*.

Namukonde, N., Simukonda, C., & Ganzhorn, J.U. (2018) Dietary niche separation of small mammals in an African Savanna. *BIOTROPICA*. doi:10.1111/btp.12537.

NPWS/JICA. (1999) *General management plan for Kafue National Parks and its surrounding game management areas.* National Parks and Wildlife Services, Chilanga, Zambia.

Rowe-Rowe, D.T. (1995) Small mammal recolonisation of a fire-exclusion catchment after unscheduled burning. *South African Journal of Wildlife Research,* **25**, 133–137.

Sieg, H.C. (1987) *Small mammals: Pests or vital components of the ecosystem*. Great Plains Wildlife Damage Control Workshop Proceedings. University of Nebraska, Lincoln, Nebraska.

Stanley, W.T. and Goodman, S.M. (2011a) Small mammal inventories in the East and West Usambara Mountains, Tanzania. 1. Study areas, methodologies and general results. *Fieldiana,* **4**, 1–17.

Stanley, W.T. & Goodman, S.M. (2011b) Small mammal inventories in the East and West Usambara Mountains, Tanzania. 4. Rodentia. *Fieldiana,* **4**, 53–73.

Stanley, W.T., Goodman, S.M. & Hutterer, R. (2011) Small mammal inventoried in the East and West Usambara Mountains, Tanzania. 2. Families Soricidae (Shrews and Macroscelididae (elephant shrews). *Fieldiana*, **4**, 18–23.

Swanepoel, C.M. (1981) The effect of fire on a small mammal community. *South African Journal of Zoology,* **16**, 232–236. doi:10.1080/02541858.1981.11447761

Swihart, R.K., Slade, N.A. & Bergstorm, B. (1988) Relating body size to the rate of home range use in mammals. *Ecology,* **69**, 393–399.

Timbuka, C.D. & Kabigumila J. (2006) Diversity and abundance of small mammals In the Serengeti Kopjes, Tanzania. *Tanzania Journal of Science*, **32**, 1–12.

Violle, C., Navas, M.L., Vile, D., et al. (2007) Let the concept of trait be functional! *Oikos,* **116**, 882–892. DOI:10.1111/j.2007.0030-1299.15559.x.

Yarnell, R.W., Scott D.M., Chimimba, C.T. & Metacalfe, D.J. (2007) Untangling the roles of fire, grazing and rainfall on small mammal communities in grassland ecosystems. *Oecologia,* **154**, 387–407. doi:10.1007/s00442-007-0841-9.

Yarnell, R.W., Metcalfe, D.J., Dunstone, N., Burnside, N. & Scott D.M. (2008) The impact of fire on vegetation type use by the short-snouted elephant shrew (*Elephantulus brachyrhynchus*) in North West Province. *African Zoology,* **43**, 45–52.

Young, H.S., McCauley, D.J., Dirzo, R. et al. (2015) Context-dependent effects of large-wildlife declines on small-mammal communities in central Kenya. *Ecological Applications,* **25**, 348–360.

ZAWA. (2013) *Kafue National Park general management plan 2013–2023, Appendix 31.* Zambia Wildlife Authority, Chilanga, Zambia.

References [CrossRef]

Begon, M., Harper, J.L., & Townsend, C.R. (2006) *Ecology*. Blackwell, Oxford.

Bösing, M.B., Haarmeyer, D.H., Dengler, J. et al. (2014) Effects of livestock grazing and habitat characteristics on small mammal communities in the Knersvlakte, South Africa. *Journal of Arid Environments*, **104**, 124–131. CrossRef

Chanda, J. (2007) *Fire management plan for Kafue National Park and its surrounding game management areas*. Zambia Wildlife Authority, Chilanga, Zambia.

Crowley, B.E. (2012) Stable isotope techniques and applications for primatologists. *International Journal of Primatology*, **33**, 673–701. CrossRef

Fry, B. (2008) *Stable isotope ecology*. Springer-Verlag, New York.

Green, S.D., Roloff, G.J., Heath, B.R., et al. (2015) Temporal dynamics of the response by African mammals to prescribed fire. *Journal of Wildlife Management*, **79**, 235–242. CrossRef

Happold, D.C.D. (2013) *Mammals of Africa. Volume III: Rodents, hares, and rabbits*. Bloomsbury, London.

Happold, M. & Happold, D.C.D. (2013) *Mammals of Africa. Volume IV: Hedgehogs, shrews, and bats*. Bloomsbury, London.

Hutchinson, G.E. (1959) Homage to Santa Rosalia, or why are there so many kinds of animals? *American Naturalist*, **93**, 137–159. CrossRef

Kalies, E.L. & Covington, W.W. (2012) Small mammal community maintains stability through compensatory dynamics after restoration of a ponderosa pine forest. *Ecosphere* **3**, 78. CrossRef

Kampamba, G., Chansa, W. & Changwe, K. (2005) *Fire management plan for protected areas in Zambia*. Zambia Wildlife Authority, Chilanga, Zambia.

Kelly, D. (2014) *A map of the Kafue ecosystem: Fire history 2000–2013*. The Nature Conservancy, Lusaka, Zambia.

MacArthur, R.H., & Levins, R. (1967) The limiting similarity, convergence, and divergence of coexisting species. *American Naturalist*, **101**, 377–385. CrossRef

Martin, G. (2003) The role of small ground-foraging mammals in topsoil health and biodiversity: Implications to management and restoration. *Ecological Management & Restoration*, **4**, 114–119. CrossRef

Moss, P. (1973) *Notes on the interim fire use and fire control programme for the Kafue National Park*. National Parks and Wildlife Services, Chilanga, Zambia.

Mwima, H. (2006) *Vegetation monitoring manual for the Kafue National Park*. Zambia Wildlife Authority, Mumbwa, Zambia.

Namukonde, N., Kuebler, D. & Ganzhorn, J. U. (2017) Differential effects of fire on small mammal communities in the Busanga Flood Plain, Zambia. *Tropical Conservation Science*, **10**, 1-13. CrossRef

Namukonde, N., Muleya, Z. & Ganzhorn, J. U. (in press) Small mammals in Kafue National Park, Zambia. *Verhandlungen des Naturwissenschaftlichen Vereins in Hamburg*.

Namukonde, N., Simukonda, C., & Ganzhorn, J.U. (2018) Dietary niche separation of small mammals in an African Savanna. *BIOTROPICA*. CrossRef

NPWS/JICA. (1999) *General management plan for Kafue National Parks and its surrounding game management areas.* National Parks and Wildlife Services, Chilanga, Zambia.

Rowe-Rowe, D.T. (1995) Small mammal recolonisation of a fire-exclusion catchment after unscheduled burning. *South African Journal of Wildlife Research*, **25**, 133–137.

Sieg, H.C. (1987) *Small mammals: Pests or vital components of the ecosystem*. Great Plains Wildlife Damage Control Workshop Proceedings. University of Nebraska, Lincoln, Nebraska.

Stanley, W.T. and Goodman, S.M. (2011a) Small mammal inventories in the East and West Usambara Mountains, Tanzania. 1. Study areas, methodologies and general results. *Fieldiana*, **4**, 1–17. CrossRef

Stanley, W.T. & Goodman, S.M. (2011b) Small mammal inventories in the East and West Usambara Mountains, Tanzania. 4. Rodentia. *Fieldiana*, **4**, 53–73. CrossRef

Stanley, W.T., Goodman, S.M. & Hutterer, R. (2011) Small mammal inventoried in the East and West Usambara Mountains, Tanzania. 2. Families Soricidae (Shrews and Macroscelididae (elephant shrews). *Fieldiana*, **4**, 18–23.

Swanepoel, C.M. (1981) The effect of fire on a small mammal community. *South African Journal of Zoology*, **16**, 232–236. CrossRef

Swihart, R.K., Slade, N.A. & Bergstorm, B. (1988) Relating body size to the rate of home range use in mammals. *Ecology*, **69**, 393–399. CrossRef

Timbuka, C.D. & Kabigumila J. (2006) Diversity and abundance of small mammals In the Serengeti Kopjes, Tanzania. *Tanzania Journal of Science*, **32**, 1–12.

Violle, C., Navas, M.L., Vile, D., et al. (2007) Let the concept of trait be functional! *Oikos*, **116**, 882–892. CrossRef

Yarnell, R.W., Scott D.M., Chimimba, C.T. & Metacalfe, D.J. (2007) Untangling the roles of fire, grazing and rainfall on small mammal communities in grassland ecosystems. *Oecologia*, **154**, 387–407. CrossRef

Yarnell, R.W., Metcalfe, D.J., Dunstone, N., Burnside, N. & Scott D.M. (2008) The impact of fire on vegetation type use by the short-snouted elephant shrew (*Elephantulus brachyrhynchus*) in North West Province. *African Zoology*, **43**, 45–52. CrossRef

Young, H.S., McCauley, D.J., Dirzo, R. et al. (2015) Context-dependent effects of large-wildlife declines on small-mammal communities in central Kenya. *Ecological Applications*, **25**, 348–360. CrossRef

ZAWA. (2013) *Kafue National Park general management plan 2013–2023, Appendix 31*. Zambia Wildlife Authority, Chilanga, Zambia.

Biodiversity

Climate, fish, and people in Zambezian fisheries, with emphasis on a natural flood cycle in the ephemeral Lake Liambezi

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Abstract: Northern Namibia is fed by the Kavango, the Kwando, and the Zambezi Rivers, which flow from Angola and Zambia. Flows fluctuate in both the short and long terms as a result of climate fluctuations, with major impacts on fish stocks. Rural communities' fishery-dependent livelihoods are thus vulnerable to impacts of climate change, illustrated here by changes in the fish and fisheries of the ephemeral Lake Liambezi over a filling, stabilisation, and recession cycle between 2009 and 2016. The fish population of the lake, after filling from the Zambezi in 2009, was initially dominated by small cyprinids, mainly *Enteromius paludinosus*, and later by other small species, notably *Brycinus lateralis*. A lucrative fishery developed for more valuable large cichlids that became well established from 2010. The establishment of the fishery led to an influx of migrant fishers and an export fish trade to Zambia and the Democratic Republic of the Congo. Lakeside communities organised fisheries committees to address management issues, and the fishery remained productive until a natural stock collapse when the lake went into recession in 2016. This followed years of low river flow that resulted in negligible inflow to the lake after 2011. In contrast to the productive Liambezi fishery, other Zambezian riverine fisheries experienced economic collapse over the same period due to rapid and uncontrolled increase in destructive fishing methods that communities appeared powerless to prevent. Management recommendations from the project's research results have now been implemented by the government and adopted by some communities, but with the likelihood of lower flood levels in future as a result of climate change, the situation remains critical. Developing proactive management approaches to maximise yields from ephemeral water bodies, while mitigating against excessive exploitation in perennial rivers, is a major challenge.

Resumo: O Norte da Namíbia é alimentado pelos rios Kavango, Kwando e Zambezi, os quais fluem de Angola para a Zâmbia. Os caudais oscilam tanto a curto como a longo prazo, como resultado das flutuações climáticas, com importante impacto nas populações de peixes. A subsistência de comunidades rurais dependentes das pescas está assim vulnerável aos impactos das alterações climáticas, ilustradas aqui pelas mudanças no peixe e na pesca no efémero Lago Liambezi ao longo de um ciclo de enchente, estabilização e recessão entre 2009 e 2016. A população de peixe do lago após a enchente do Zambezi em 2009 foi inicialmente dominada por pequenos ciprinídeos, *Enteromius paludinosus*, e posteriormente por outras pequenas espécies, nomeadamente *Brycinus lateralis*. Uma pesca mais lucrativa desenvolveu-se com base em ciclídeos maiores e mais valiosos que se estabeleceram em 2010. O estabelecimento da pesca resultou num influxo de pescadores migrantes, com um comércio de exportação de peixe para a Zâmbia e a República Democrática do Congo. As comunidades junto ao lago organizaram comités de pesca para abordar questões de gestão e as pescas permaneceram produtivas até ao colapso natural da população, quando o lago iniciou a recessão em 2016. Esta resultou dum período de reduzidos fluxos fluviais, que resultaram num influxo negligenciável para o lago após 2011. Em contraste com as produtivas pescas de Liambezi, outras actividades pesqueiras ribeirinhas Zambezianas verificaram o colapso económico durante o mesmo período, como resultado de um aumento rápido e descontrolado do uso de métodos destrutivos de pesca que as comunidades não conseguiram prevenir. Recomendações de gestão provenientes dos resultados da investigação do projecto foram implementadas pelo governo e adoptadas por algumas comunidades. No entanto, com a probabilidade de níveis de inundação mais baixos no futuro devido às alterações climáticas, a situação mantém-se crítica. O desenvolvimento de abordagens de gestão proactivas para maximizar rendimentos dos corpos de água efémeros, enquanto mitigam a exploração excessiva em rios perenes, representa um grande desafio.

Introduction

Namibia is an arid country, and rainfall in the northern regions is inadequate to generate perennial rivers. These regions are, nevertheless, well-watered by a highly complex system of rivers (Kavango, Kwando, and Zambezi) that flow from the southern highlands of Angola, with Zambezi flow augmented by a number of large tributaries in northern Zambia (Fig. 1 and 2). These rivers feed floodplains, swamps, and ephemeral lakes in the north of Namibia. In years of unusually high flood levels, the three river systems are interlinked. The Okavango Delta links to the Kwando/Linyanti swamps via the Selinda spillway, and the Kwando links through the Linyanti Swamp and Lake Liambezi to the Chobe and thence to the Upper Zambezi (Skelton, 2001). Thus, the river systems largely share the same fish fauna, though with some local endemics, particularly in headwater tributaries.

Because the scale of annual flooding reflects rainfall intensity hundreds of kilometres to the north, independent of climate variability in Namibia itself, changes in the extent and intensity of Namibia's rainfall have a minimal impact on these rivers.

There are long-term variations in the scale of annual flooding in these rivers, seen in the Zambezi river level data from Victoria Falls (Fig. 3). From the late 1940s to the end of the 1970s, average annual rainfall was much higher than in the preceding decades and in the years since 1980. This places in perspective the floods of 2009 and 2010 that were considered to be "disastrous" floods in Namibia. They were in fact normal, with peaks comfortably exceeded in 1948, 1952, 1957, 1958, 1961, 1963, 1969, and 1978. The major variations in flooding will obscure impacts, if any, of anthropogenic climate warming on the fisheries. Instead, we illustrate the impacts of natural changes in the aquatic environment on fish and fisheries. The major focus is on the changes in the dynamics of the fish and fisheries of Lake Liambezi over the last decade as the fish populations and fishery of this large floodplain lake responded to a natural cycle that is

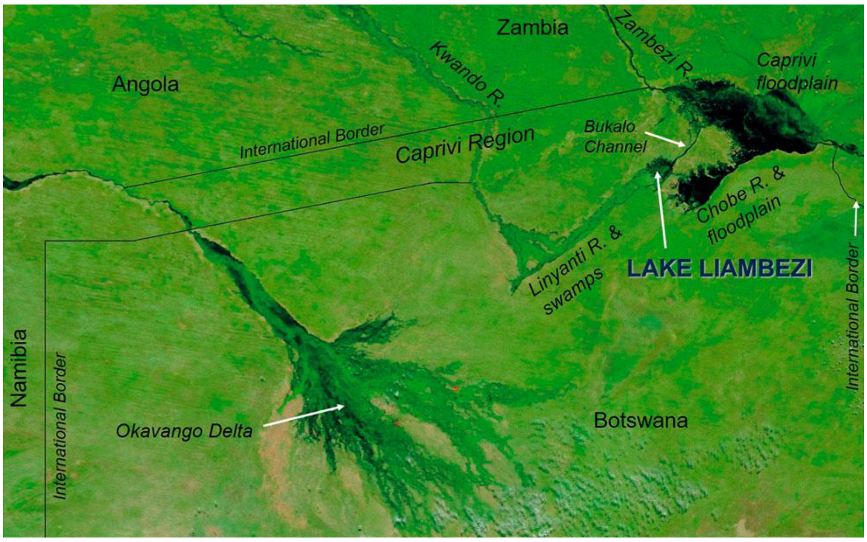

Figure 1: Satellite photo of the Zambezi, Kwando, and Kavango River systems taken at high water in May 2009, showing their interrelationships and the position of Lake Liambezi, the main focus of this chapter (from Tweddle et al., 2011, satellite photo © NASA Earth Observatory).

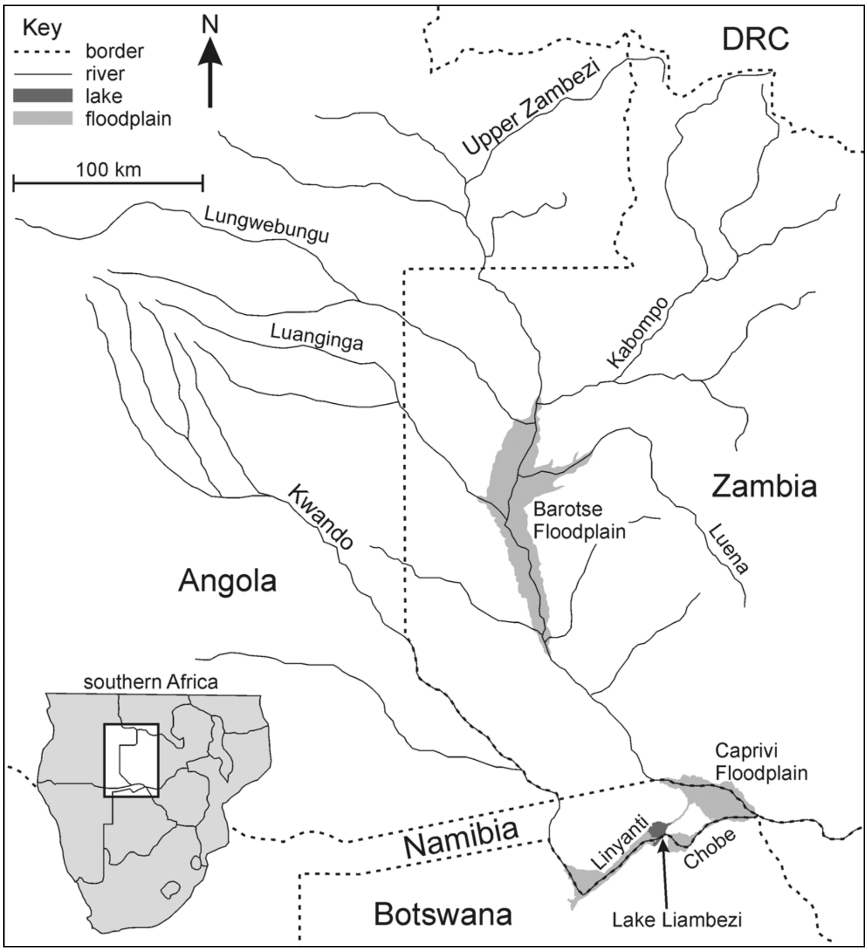

Figure 2: The Upper Zambezi system, showing the location of the major floodplains and Lake Liambezi (from Peel, 2017).

a microcosm of what might be expected to occur in the larger system as a whole if the rivers and floodplains are reduced in area and volume as a result of longer-term climate changes that are projected for the region (Midgley et al., 2005; Turpie et al., 2010). Lake Liambezi is ephemeral, undergoing cyclical phases of flooding and drying (Peel et al., 2015b). Prior to the most recent full phase, an earlier period of inundation lasted from circa 1966 until, after five consecutive years of

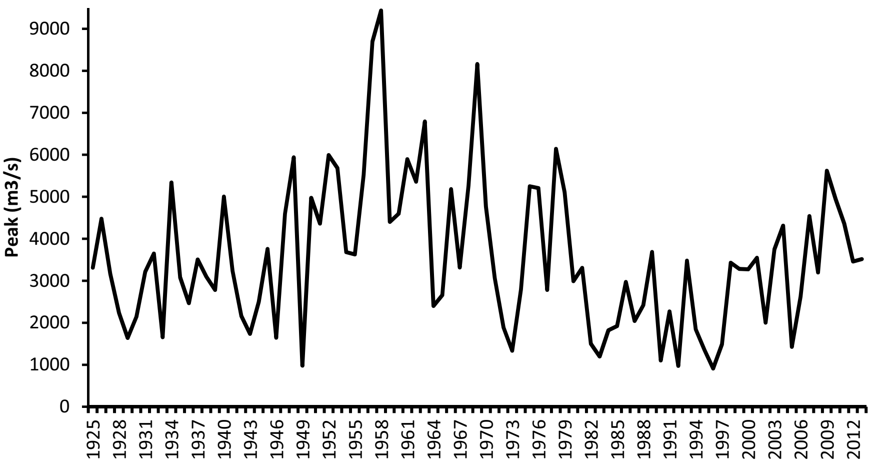

Figure 3: Peak 5-day average flow rates per year of the Zambezi River at Victoria Falls.

low floods, it dried up in 1985 (Grobler & Ferreira, 1990). The lake supported an important commercial fishery through the 1970s, yielding over 600 tonnes in 1974 (van der Waal, 1980). These catches were greatly exceeded in the most recent period of inundation, starting in 2007, through complete inundation in 2009; thereafter the lake saw declining water levels and was near drying out by the end of 2016.

There is usually a direct correlation between the size and scale of annual flooding in river/floodplain fisheries and fish yields (Welcomme & Hagborg, 1977). Large floods lead to high recruitment because of the greatly increased breeding and nursery areas, and this is reflected in catches. In some cases there is a time lag, depending on the rate of growth of the fish species, the size at recruitment to the fishery, and the fishing intensity. There may be a direct correlation between the scale of flood and catches in the same year in cases where the fishery is based on young of the year or short-lived fish species (e.g., Lae, 1992; Halls, 1998; Tweddle, 2015), or there may be a time lag of 2–4 years (Welcomme, 1978, 2001) between high floods and consequent high yields where the fishery is for longer-lived species.

In addition to the impact of annual and long-term natural flood cycles, fishing effort has a major impact on the fish faunal assemblages. The freshwater fisheries of Namibia and its neighbouring countries are under increasing pressure, resulting in overexploitation of the resources (Tweddle, 2010; Tweddle et al., 2015). In this chapter, we discuss the biodiversity and complex dynamics of the riverine and floodplain ecosystems and the livelihood strategies of riparian and floodplain dwellers and their dependence on the resources. Understanding of the complex interrelationships of climate, fish, and people is essential for management of these vitally important resources. The lessons learned through the research and through existing management programmes in north-eastern Namibia should contribute to effective fisheries management mechanisms throughout the region.

Research approach

The SASSCAL programme provided the opportunity for an interdisciplinary research approach that applied fisheries and social survey data to better understand the fish populations of the rivers, floodplains, and lakes of north-eastern Namibia and south-western Zambia in relation to both fisheries yields and potential climate change impacts. In Lake Liambezi, changes in fish populations during filling, stabilisation, and recession were studied using a range of standardised experimental fishing gears, of which a standardised fleet of gillnets with 11 different mesh sizes was the main sampling gear. Sampling was conducted quarterly during the SASSCAL programme (Peel, 2017) and was supplemented by recording fishers' catches at Shamahuka landing site. The ecology of key fish species and population dynamics in relation to the productivity of the system and food web structure changes over time were researched in depth, including age, growth, and reproductive studies of the key fishery species to assess their vulnerability to fishing (Peel, 2017; Taylor, 2017). Structured interviews with lakeshore communities, fishers, and traders elucidated the impacts of changing dynamics in the Lake Liambezi fishery on fishing communities. The river and floodplain fisheries were assessed through the use of community-based monitors and standardised research netting. Low-water and high-water sampling and catch assessment surveys were conducted for the Barotse floodplain (Fig. 2) fishery in Zambia.

Lake Liambezi

The Lake Liambezi wetland system covers some 300 km^2, of which 100 km^2 is open water when the lake is full (Seaman et al., 1978; Peel et al., 2015b). The lake is shallow, with an average depth of approximately 2.5 m and a maximum depth of 7 m at its peak in 2010. It receives water from several sources. The primary source is the Zambezi River, whose waters enter the lake during years of high flooding from two directions. Annually, when the Zambezi floods, the Chobe River reverses flow direction and enters the lake from the south-east, while the Bukalo Channel flows from the Zambezi River floodplains into the north-east of the lake. The Kwando River flows south from Angola into the Linyanti wetlands to the west of the lake. Its waters percolate through the wetlands and out via the Linyanti Channels, which flow eastward along the Namibia–Botswana border into the lake. Rainfall and runoff from the area north of the lake also contribute water inputs. Outflow from the lake via the Chobe River when floodwaters recede is intermittent and dependent on lake level.

Lake Liambezi was inundated from ~1966 until 1985 (Grobler & Ferreira, 1990); since then it has remained mainly dry until receiving moderate inflow in 2007, and then filled completely in the 2009 flood. After further inflow in 2010 and 2011, it has not received inflow since, and dried to shallow turbid lagoons by

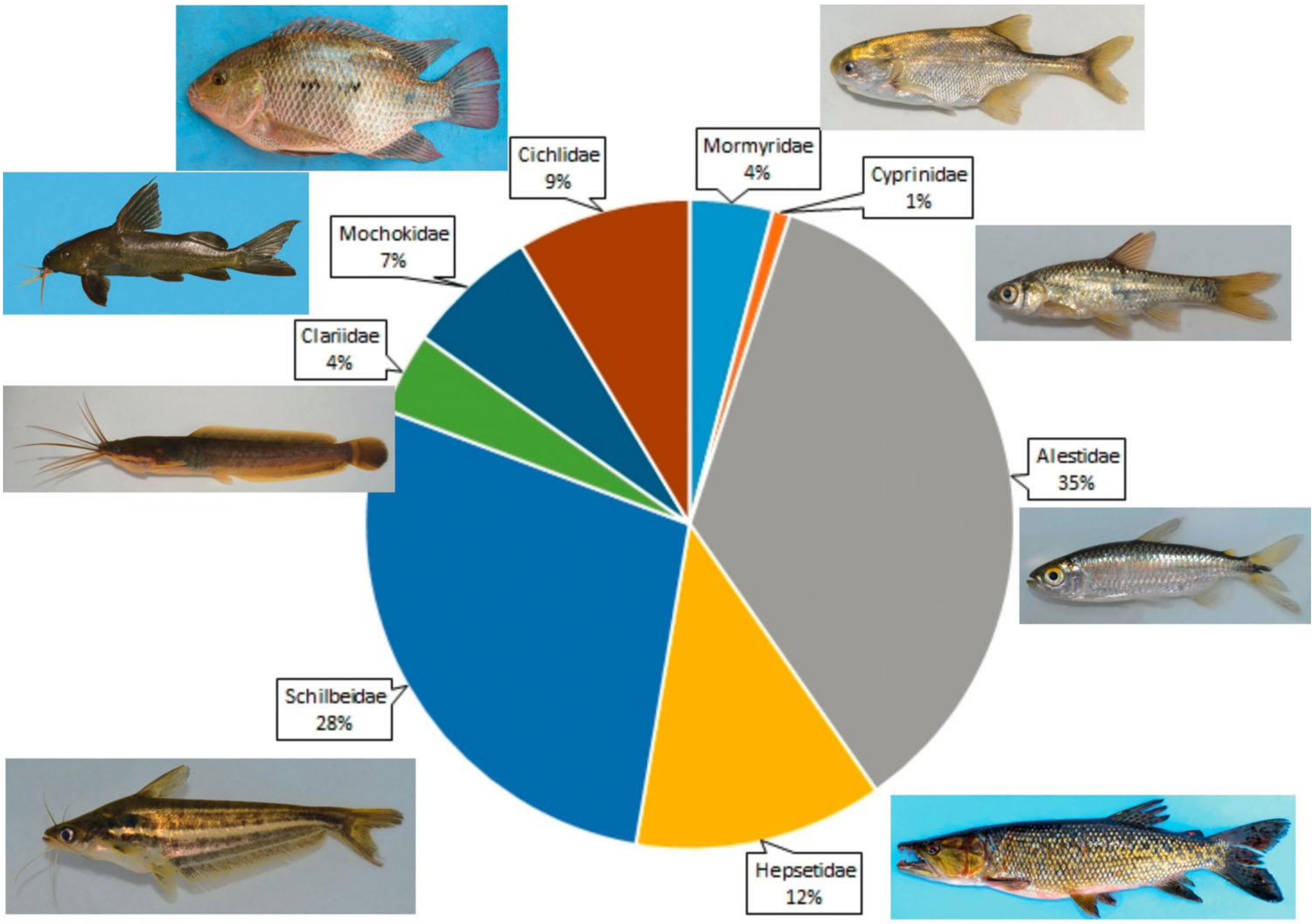

Figure 4: Percentage contribution by weight of the fish families. Illustrated with common species representative of the experimental gillnet catches in Lake Liambezi, 2013–2014. The commercially important large cichlids made up only 9% of the overall catch, whereas the small alestid *Brycinus lateralis* made up 35% of the catch. Species illustrated: Cichlidae — *Oreochromis andersonii*; Mormyridae — *Petrocephalus* cf. *okavangensis*; Cyprinidae — *Enteromius paludinosus*; Alestidae — *Brycinus lateralis*; Hepsetidae — *Hepsetus cuvieri*; Schilbeidae — *Schilbe intermedius*; Clariidae — *Clarias gariepinus*; Mochokidae — *Synodontis nigromaculatus*.

late 2016. This chapter reports on the major collaborative research programme that followed the complete filling, stabilisation, and recession of the lake over that time.

Fish assemblage in Lake Liambezi and changes over time

In the period from inundation of the lake in 2007 to 2009 to recession in 2016, the fish assemblage of Lake Liambezi underwent a succession from a colonising assemblage dominated by floodplain specialists to a relatively stable lacustrine assemblage. The evolution of the fish community was characterised by three distinct phases. The first phase involved the inundation and colonisation of the lake in 2007, followed by its decline up until the floods that filled the lake in 2009. During this phase the lake was colonised by fishes from the Zambezi and Chobe floodplains, composed predominantly of cyprinids, notably the straightfin barb, *Enteromius paludinosus*; the dashtail barb, *E. poechii*; the catfishes *Schilbe intermedius* and *Clarias gariepinus*; and the bulldog *Marcusenius altisambesi*. These are specialists at colonising newly flooded environments. Following inundation, the water level declined, concentrating fishes in an increasingly harsh environment that resulted in high mortality from both abiotic drivers and fishing. The filling of the lake in the March 2009 floods marked the beginning of the second successional phase. The initial main coloniser, *E. paludinosus,* saw a significant decline in abundance despite the possibility of external recruitment from the neighbouring floodplains. The slender robber, *Rhabdalestes maunensis*, underwent explosive population growth between 2009 and 2010 but crashed equally rapidly within a year. The striped robber, *Brycinus lateralis,* surpassed its smaller relative and went on to dominate the fish community. This marked the beginning of a third phase, in 2011, as the fish community began to approach a more stable state. Larger, slower-growing species increased steadily in abundance, highlighted by the development of the fishery, based primarily on large tilapiine cichlids. From 2011 to 2014, the fish community was dominated by *B. lateralis* and *S. intermedius*. These two species made up 63% of the fish by weight in the experimental fishing gears by 2014 (Fig. 4) (Peel et al., 2015a). By 2016, however, the lake went into recession. Unfortunately no data are available on the changing fish community during that time. Plates 1 and 2 illustrate all species recorded in the lake during the project research programme.

Plate 1


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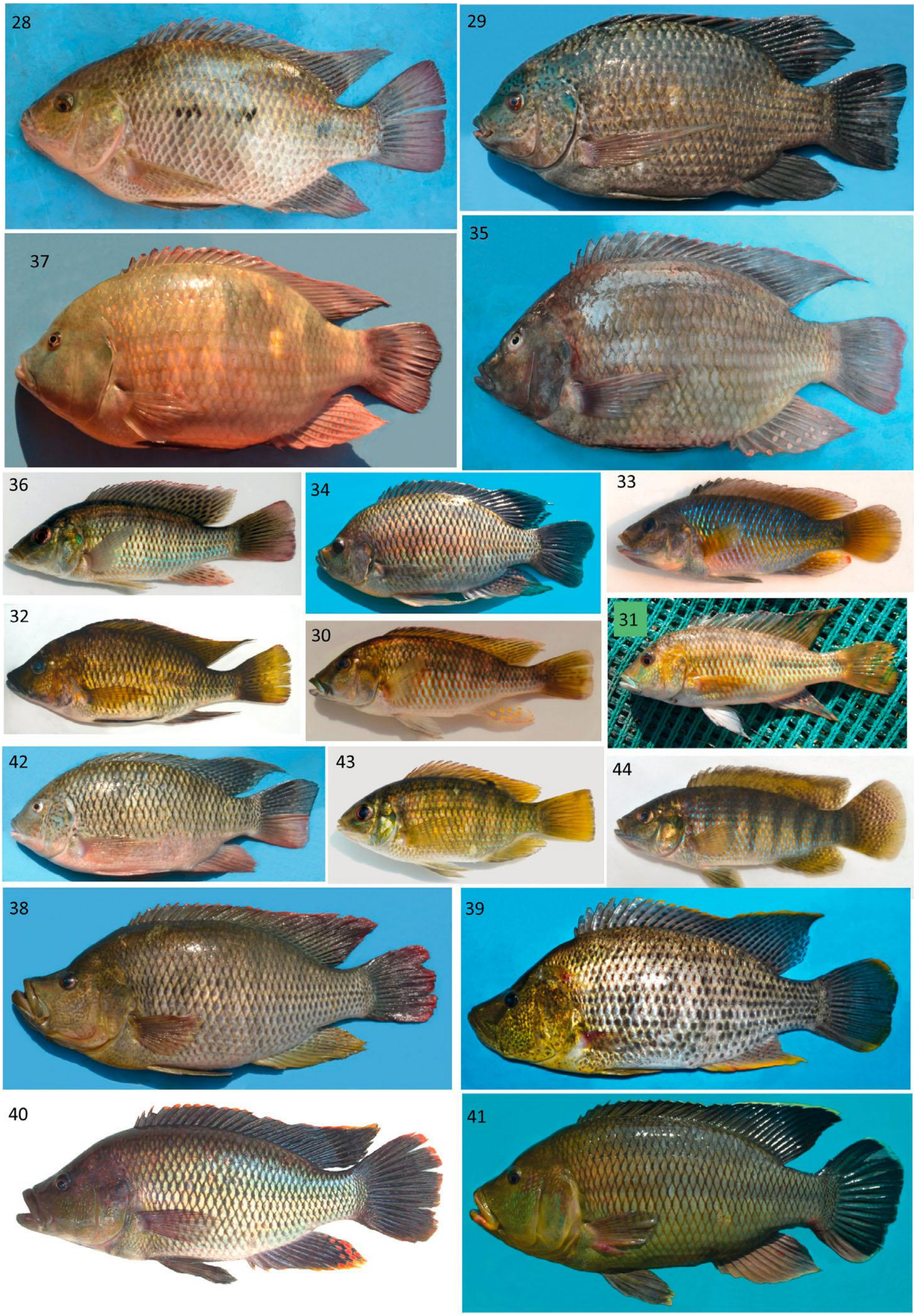
Plate 2



Plates 1 and 2: Photographs of all fish species recorded from Lake Liambezi during the course of the project. This list represents approximately half of the total number of species known from the neighbouring Upper Zambezi floodplains. The number on each photo identifies the fish as in this list. Scientific names are listed, plus an indication of average adult total length in cm. Several species need further taxonomic study, particularly the large *Pharyngochromis* species.

No	Species scientific name	Length (cm)
	Mormyridae	
1	*Marcusenius altisambesi* (Kramer, Skelton, van der Bank & Wink, 2007)	20
2	*Mormyrus lacerda* (Castelnau, 1861)	40
3	*Petrocephalus* cf. *okavangensis* Kramer, Bills & Skelton, 2011	10
4	*Pollimyrus* cf. *cuandoensis* Kramer, van der Bank & Wink, 2014	7
	Cyprinidae	
5	*Enteromius barnardi* (Jubb, 1961)	4
6	*Enteromius bifrenatus* (Fowler, 1935)	7
7	*Enteromius haasianus* (David, 1936)	3
8	*Enteromius multilineatus* (Worthington, 1933)	4
9	*Enteromius paludinosus* (Peters, 1852)	10
10	*Enteromius poechii* (Steindachner, 1911)	10
11	*Enteromius radiatus* (Peters, 1853)	7
12	*Enteromius unitaeniatus* (Günther, 1866)	7
13	*Coptostomabarbus wittei* (David & Poll, 1937)	3
14	*Labeo cylindricus* Peters, 1852	20
15	*Labeo lunatus* Jubb, 1963	30
	Alestidae	
16	*Brycinus lateralis* (Boulenger, 1900)	10
17	*Micralestes acutidens* (Peters, 1852)	6
18	*Rhabdalestes maunensis* (Fowler, 1935)	5
19	*Hydrocynus vittatus* Castelnau, 1861	50
	Hepsetidae	
20	*Hepsetus cuvieri* Castelnau, 1861	30
	Schilbeidae	
21	*Schilbe intermedius* Rüppell, 1832	28
	Clariidae	
22	*Clarias gariepinus* (Burchell, 1822)	100
23	*Clarias ngamensis* Castelnau, 1861	60
24	*Clarias stappersii* Boulenger, 1915	30
25	*Clarias theodorae* Weber, 1897	25
	Mochokidae	
26	*Synodontis nigromaculatus* Boulenger, 1905	30
27	*Synodontis* spp.	25
	Cichlidae	
28	*Oreochromis andersonii* (Castelnau, 1861)	35
29	*Oreochromis macrochir* (Boulenger, 1912)	30
30	*Pharyngochromis acuticeps* (Steindachner, 1866)	12
31	*Pharyngochromis* sp. 1	20
32	*Pharyngochromis* sp. 2	20
33	*Pseudocrenilabrus philander* (Weber, 1897)	7
34	*Sargochromis carlottae* (Boulenger, 1905)	25
35	*Sargochromis codringtonii* (Boulenger, 1908)	30
36	*Sargochromis greenwoodi* (Bell-Cross, 1975)	25
37	*Sargochromis giardi* (Pellegrin, 1903)	35
38	*Serranochromis altus* Winemiller & Kelso-Winemiller, 1990	40
39	*Serranochromis angusticeps* (Boulenger, 1907)	25
40	*Serranochromis macrocephalus* (Boulenger, 1899)	20
41	*Serranochromis robustus jallae* (Günther, 1864)	40
42	*Coptodon rendalli* (Boulenger, 1896)	25
43	*Tilapia ruweti* (Poll & Thys van den Audenaerde, 1961)	9
44	*Tilapia sparrmanii* A. Smith, 1840	14
	Poeciliidae	
45	*Micropanchax hutereaui* (Boulenger, 1913)	2
46	*Micropanchax johnstoni* (Günther, 1893)	5
47	*Micropanchax katangae* (Boulenger, 1912)	4
48	*Micropanchax* sp. 'pygmy topminnow'	2
	Anabantidae	
49	*Ctenopoma multispine* Peters, 1844	6

The Lake Liambezi fishery

Until 2016, when the lake entered a drying phase, the fishery targeted large cichlid species, most notably the tilapiines *Oreochromis andersonii*, *O. macrochir*, and *Coptodon rendalli*, together with the predatory *Serranochromis macrocephalus*. To catch these fishes, the most common mesh sizes used in gillnets were between 89 and 114 mm (Peel et al., 2015b). Unlike those in other fisheries in the region, such as the Upper Zambezi including the Barotse Floodplain in Zambia, the Lake Liambezi fishers did not follow a trend towards using ever smaller mesh sizes; as a result, the fishery remained healthy and economically productive until the lake recession in 2016. Plates 3 and 4 illustrate the changes in the lake and fishery over time. Commercial gillnet catch per unit effort (CPUE) varied seasonally, being lower during summer from October to January. Overall, the CPUE estimated from the commercial fishers, averaging 7 kg per 100 m net per night was significantly higher than that recorded by independent sampling using similar monofilament gillnets. This reflected the fishing methods used by the commercial fishers. Although illegal, driving fish into nets by bashing the water (known as *kutumpula*) and by actively using the nets as seines were widely used techniques. In total, 343 canoes were counted in the lake in May 2013. Assuming that all canoes were used for fishing, and extrapolating from the quantity of fish brought in per day by each dugout canoe at Shamahuka landing site in 2011 and 2012 (mean catch 36 kg), the annual yield of the fishery for 2011/2012 is estimated to have been 2,700 tonnes.

As the fishery targeted the larger, economically valuable cichlids, which in fact comprised only 9% of the fish biomass (Fig. 4), it was proposed to develop a 25 mm mesh surface gillnet fishery for the striped robber, *B. lateralis*, because of its abundance (Fig. 4), palatability, and ease of marketing (Peel et al., 2015a). Research netting proved that it was feasible to establish such a fishery without affecting the stocks of the economically important large cichlids, as the surface-set nets caught almost entirely *B. lateralis* and a negligible quantity of juvenile cichlids (photos in Plate 4). The establishment

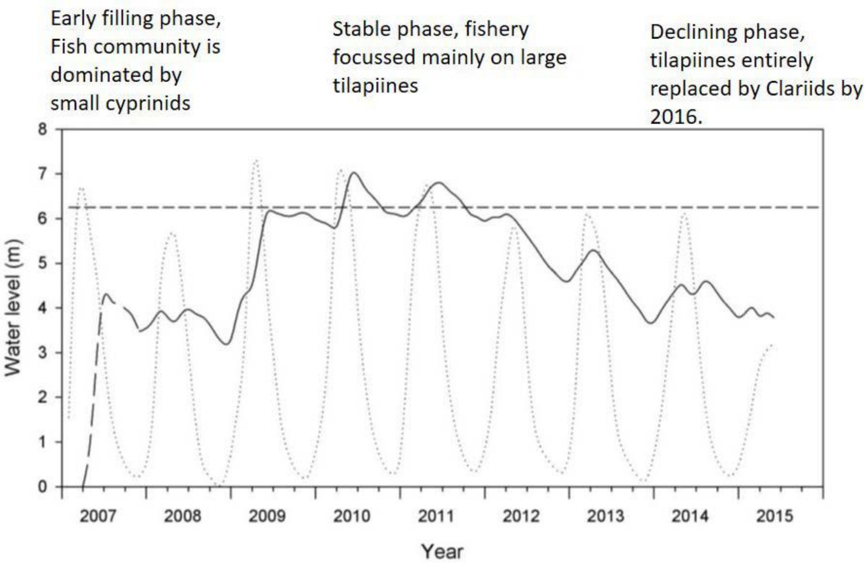


Figure 5: Water level of Lake Liambezi (——) since inundation starting in 2007 (dashed line at beginning as no data). The annual flood cycle of the Zambezi River (··········) and the level at which the Zambezi River spills into the lake (- - - - -) are illustrated to show when the lake received inflow. The phases of the fishery are described above the chart.

of such a fishery would have required changes to Namibia's fisheries regulations, as such small meshes are currently illegal (MFMR, 2003). The lake, however, entered a rapid drying phase by 2016 and plans for such a fishery were therefore shelved (Peel et al., 2015a). The changes in lake level and consequent changes in the fishery are summarised in Figure 5.

With the lake receding in 2016 to a series of small turbid lagoons, the cichlids disappeared from the catches and the drying lagoons yielded instead large quantities of catfish, *C. gariepinus* and *C. ngamensis*. No direct catch recording system was in place at this time, but enormous quantities were being salted and dried and exported through Zambia to the DRC (Plate 4).

Timeline of events in the Lake Liambezi Fisheries (2001 to 2017)

In addition to the biological and fisheries studies on Lake Liambezi, the fishing communities around the lake were a major focus of study (Murphy, 2017). Because the lake is ephemeral, communities have to be flexible in their livelihood strategies, switching from land-based sources of food and income to lacustrine sources as the lake rises and falls. To manage the harvesting of natural resources at optimum levels, research focused on the fishing communities along the lakeshore.

2001 – Lake started filling from the Chobe River and fishing started at the inflow.

2003 – Bukalo Channel flowed into lake for first time in twenty years.

2006 – Water entered the lake from the Linyanti River to the west.

2008 – Fish from Lake Liambezi traded at Katima Mulilo market.

2009 – Big flood filled lake. At Muyako village, influx of migrant fishers and traders (mainly foreign nationals, especially Zambians) and Namibian-owned small-scale fishing enterprises proliferated — traders supplied gear and hired fishers. Because of increased competition for fish, illegal fishing methods started and proliferated — bashing (*kutumpula*) and dragnetting (*ituwa*). Muyako Traditional Authority called community meeting, leading to election of Muyako Fish Committee.

2010 – Floods maintained high lake level. Widespread use of monofilament gillnets, replacing former less efficient multifilament nets (mono- is single-strand, almost transparent nylon; multi- is nylon twisted thread). Three tonnes per day of fresh fish passed through Katima Mulilo market, with 90% from Lake Liambezi. Lake yielded 1,000 tonnes per year of high-value tilapias (Tweddle et al., 2011). Trading dominated by Zambian nationals with fish loaded at the lakeside. Lakeside harbours, especially Shamahuka, grew to sizable settlements. Masokatwani Fish Committee was established in response to excessive exploitation. Namibian Ministry of Fisheries and Marine Resources (MFMR) and police (NamPol) active in the lake, enforcing fisheries and immigration regulations.

2011 – Floods maintained high lake level. To regulate the fish trade, Zambian trucks transporting dried and salted fish were relocated from lakeside villages to the Zambian border. Namibian traders from Masokatwani used fish trade corridor through Zambia to DRC for the first time.

2012 – Mainly monofilament nets in use. Estimate of 2,700 tonnes as annual yield in lake in 2011/2012, 4.5 times more than the 600 tonnes recorded in 1974 (Peel et al., 2015b).

2013 – Lusu and Zilitene/Kwena Fish Committees established. New road to Zilitene allowed for fish trading from Zilitene to switch from Muyako to lakeside harbours at Zilitene. Security forces enforced immigration regulations and deported illegal foreign migrants.

2014 – Helicopter used in support of government agencies engaged in curbing illegal activities.

2015 – Water level dropped. Closed season implemented in Namibia for the first time (December to February).

2016 – Water level continued dropping. Farmed fish (Nile tilapia from fish farm in Livingstone, Zambia) now sold at Katima Mulilo market as fish supply from Lake Liambezi dried up. Ban on use of monofilament nets implemented by MFMR.

2017 – Lake drying up. Lack of fish supply to Katima Mulilo market from Lake Liambezi caused fish price to soar.

Box 1: A historical summary of the changes that took place in the communities adjacent to the lake over the period from 2001, when some water first entered the lake after it had been effectively dry since 1985, until the study ended in 2016. The information is derived from participatory meetings conducted at four major fishing communities around the lake in 2016.

Plate 3

Lake Liambezi shortly after filling in 2010, showing extensive areas of flooded terrestrial vegetation and few canoes at landing site.

Catch of clariid catfishes in early filling phase of lake.

Anglers assisting research on fish species composition at flooded village.

Shamahuka fish landing site during fishery peak, 2012.

Good catch of large cichlids at Shamahuka, 2012.

Cichlids being sundried on rack at lakeshore for transport to market.

Fresh cichlids from Lake Liambezi being loaded with ice on truck for export to Zambia, Katima Mulilo market.

Valuable catch of large cichlids from Lake Liambezi when the lake was full and the fishery at its peak. Inset: Catches being weighed at the landing as part of the research programme.

Plate 4


Launching SASSCAL research boat on Lake Liambezi.


Successful experimental gillnetting (25 mm mesh) for *Brycinus lateralis*.


Successful experimental gillnetting (25 mm mesh) for *Brycinus lateralis*.


Salted catfish from Lake Liambezi being sundried in preparation for export to DRC, October 2016.


Dried salted catfish from Lake Liambezi being packaged at the Wenela Border Post between Namibia and Zambia for onward transport to the DRC, October 2016.


Abandoned canoes and fishing nets on shore of receding Lake Liambezi, October 2016.


Muddy turbid lagoon remaining as Lake Liambezi dries out, November 2016.

Biodiversity

Figure 6: GoogleEarth image of the dry bed of Lake Liambezi in December 2006, showing a patchwork of agricultural fields (© GoogleEarth).

Changes in the status of Lake Liambezi: the fishery in relation to community livelihoods

Prior to inundation, the main source of livelihoods was dry-land cropping (Fig. 6), with cattle ownership for wealthier households. Livelihood strategies changed considerably with the inundation of the lake as local residents were deprived of their farmlands in the fertile soils of the pre-inundated lake basin. Some local residents around the lake switched their livelihoods from dry-land cropping (with consumption and sale of surplus maize) to fish harvesting (with consumption and sale of fish). This was highly advantageous, as fish could be harvested throughout the year whereas maize is harvested and sold once a year. This had a major positive impact on livelihoods in general. While women in Namibia do not traditionally fish using boats and nets, the opportunity arose for them to trade in fish. To maximize returns, some local traders, including women, transported fish to the places commanding higher prices than markets at the lakeshore or in Katima Mulilo, and even took dried, baled fish to Kasumbelesa on the Zambia–DRC border for onward export into the Democratic Republic of the Congo.

Resource-poor households in Muyako village, as determined by a participatory wealth-ranking exercise among 145 households (Murphy, 2017), did not have access to resources to fish (e.g., labour, makoros, nets) but did, however, benefit from easy access to a protein-rich food at a relatively cheap price compared to pre-inundation times. With the exception of Muyako, all other villages had households that hired fishers.

Although the restoration of the Liambezi fishery brought considerable benefits to the communities, there were problems with the management of the fishery (Tweddle et al., 2015). The high catches resulted in an influx of fishers from outside the area, mainly from neighbouring Zambia, and thus very high fishing effort. While continuing to use the optimum mesh sizes in their nets, the fishers increasingly resorted to illegal and destructive fishing methods to maintain catch rates, including seine netting and *kutumpula*. Fishing camps on islands also became health hazards and centres for illegal activities. In response, government authorities made some coordinated campaigns to remove illegal migrants, while communities formed their own management committees, incorporating village headmen and working with the Traditional Authority (Murphy, 2017). These committees had varying degrees of success. The Muyako committee, for example, was initially successful in controlling the fishery, registering all fishers in their area and setting mesh size regulations stricter than those under the Fisheries Act (Tweddle et al., 2012). Despite problems created by the increased pressures on the fishery with the influx of migrant fishers, the committees continued to have an influence and with help from law enforcement bodies (through the MFMR Inspectorate) maintained the large cichlid fishery until the lake recession.

The drying up of Lake Liambezi through 2016 and 2017 had a negative impact on local people's livelihoods. Local residents are now returning to dry-land cropping and the sale of natural products including reeds, grass, poles, devil's claw, and thatching grass, but these activities do not adequately replace the livelihood value of the fishery. The negative livelihood impact of the drying up of the lake is severe and is expected to lead to problems such as an increase in hunger and theft.

Trends in the other inland fisheries of the region

Zambezi/Chobe floodplain

Until recently, studies on the fisheries of the Upper Zambezi River and associated floodplains were sparse, with no data on the status of the fishery prior to annual experimental gillnetting that began in 1997 (Hay & van der Waal, 2009). Their data suggested very intense fishing effort on the larger cichlid species. It was not until 2010 that any fish catch data were collected (Tweddle et al., 2015), using local villagers to record any fish catches they saw on twice-weekly walking patrols in the Zambezi/Chobe floodplains. Such data can be used to show trends in a fishery but are inadequate to conclusively demonstrate trends on their own. In this case they highlighted a dramatic decline in catches from 2010 to 2012, despite high floods that should have boosted recruitment (Tweddle et al., 2015). This agreed with trends demonstrated in the annual experimental gillnetting programme conducted by MFMR with support from Namibia Nature Foundation fisheries projects including SASSCAL. From 2010 to 2012 the catch rates declined by approximately 75% despite a rapid change in the fishery from using multifilament nylon nets to monofilament (Fig. 7, from Tweddle et al., 2015). The monofilament nets are more than three times as effective as multifilament in this area (Peel et al., 2015b), indicating that fish stocks in the Upper Zambezi River in the Zambezi/Chobe floodplain area had declined by more than 90%. More recent research data confirm that the catches have shown no sign of recovery (F. Jacobs, pers. comm.).

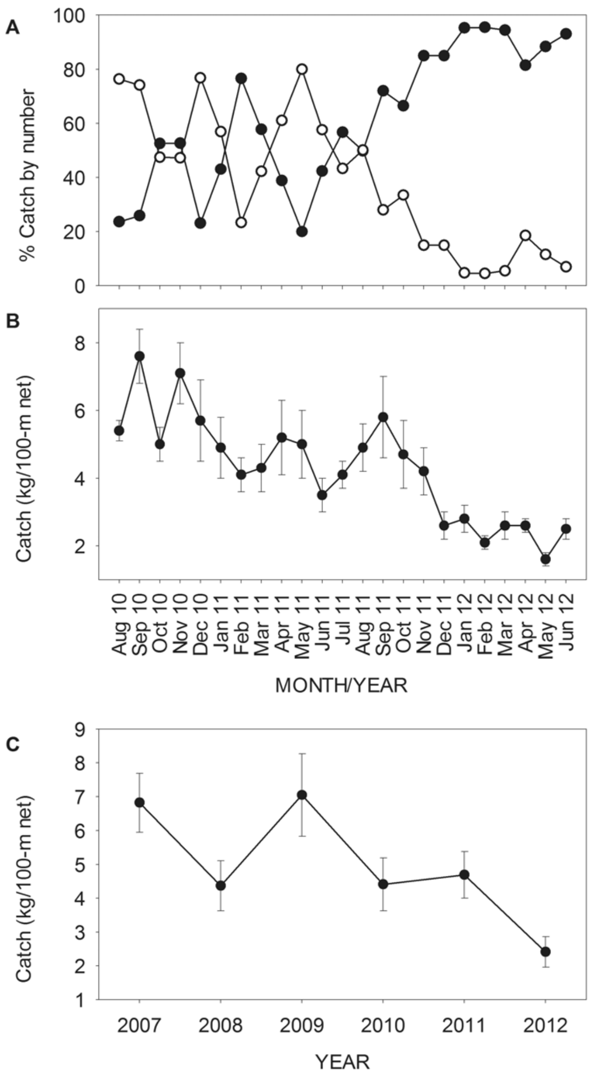


Figure 7: Evidence for decline in CPUE in the Upper Zambezi River fishery in the Zambezi/Chobe floodplain area. (a) Change from multifilament (open circles) to monofilament (closed circles) netting, demonstrated by the percentage of fish caught in each mesh type (data from community monitors). (b) Decline in CPUE in the fishery, all netting combined as passive and active gears not adequately differentiated (data recorded by community monitors). (c) Decline in CPUE in MFMR experimental gillnet catches at standard stations along the Zambezi River (source: Tweddle et al., 2015).

Central Barotse Floodplain, Zambia

Until recently, few studies had been made on the Central Barotse Floodplain (CBF) fishery in Zambia, upstream from the Zambezi/Chobe floodplains (Fig. 2), despite its enormous area and the dependence of the local population on its fish resources (Tweddle et al., 2015). Apart from outdated FAO reports (Duerre, 1969; Kelley, 1968; Weiss, 1970), a descriptive report by Bell-Cross (1974), and fish ecology studies by Winemiller (1991) and Winemiller & Kelso-Winemiller (1994, 1996), little information was available on the CBF fishery before fish biodiversity surveys carried out in 2002–2003 (Tweddle et al., 2004). At that time, the Barotse Royal Establishment and local fishing community leaders expressed great concern about declining yields and, more worrying, inappropriate fishing methods. Fishing pressure was intense, particularly in areas of relatively high human population, and the concentration of fishermen was much higher than reported previously (Welcomme, 1985). Because of the concerns raised by Tweddle et al. (2004, 2015), low- and high-water surveys of the fish and fisheries were incorporated into the SASSCAL research programme.

The low-water survey was reported on by Peel et al. (2014). They reported very low catches and a fishery based on small species, with a notable absence of the larger cichlid species that are the most economically important species in the fishery. The subsequent high-water survey conducted by D. Tweddle in May 2017 confirmed that the fishery was severely overfished both economically and biologically.

The fishing methods observed in use were fine meshed monofilament gillnets and dragnets made of shade cloth lined with cotton cloth, known as *sefa-sefa* (meaning 'sieve'). Over 50% of the observed catches were juvenile tigerfish, *Hydrocynus vittatus*, about 20 cm long, with most of the rest being small cichlid species, particularly the banded tilapia, *Tilapia sparrmanii*, and the banded jewelfish, *Hemichromis elongatus*. Experimental gillnetting yielded only small numbers of juvenile tigerfish and almost nothing else.

Like the Zambezi/Chobe floodplains, therefore, the CBF fishery is severely overfished, both biologically and economically. There is, however, one fishery area adjacent to the CBF where community fishery management works well. Over 200 pans in Liuwa Plain National Park adjacent to the CBF are managed through the system of Traditional Authority exercised by the Barotse Royal Establishment. Through this system, in cooperation with the park management, the pans are overseen by village headmen (called *indunas*), who control access rights and time of fishing (Peel et al., 2013). The successes of community participation in management in Liuwa Plain National Park and around Lake Liambezi demonstrate potential for similar management initiatives elsewhere in the system, although the problems faced in the larger floodplain systems are on a much greater scale.

Biodiversity

Management recommendations based on the results of the SASSCAL research programme

Lake Liambezi

The fish stocks of Lake Liambezi during phases of inundation are largely independent of the adjacent river and floodplain fisheries (Peel, 2017). The species composition of the fish fauna differs between different periods of inundation, and changes over time as the lake fills, stabilises, and then goes into recession. Because of this, fisheries in the lake must be managed independently of the fisheries of neighbouring river systems. The lake, when full, is a highly productive fishery for valuable large cichlid species (Peel et al., 2015). Based on the results of the SASSCAL-supported research on the biology of the key species (Peel, 2017; Taylor, 2017), the fishery over the latest period of inundation used nets with the optimum mesh size for the species involved and thus maintained a productive and economically lucrative fishery until the major lake recession of 2016. The response of the communities was encouraging, with the establishment of a number of community fisheries management committees in conjunction with the Traditional Authorities. Some of these committees were set up with advice from MFMR and the Namibia Nature Foundation (NNF) fisheries programme, while others were formed independently in response to perceived problems in the fishery. These committees developed their own regulations, and in future when the lake is full it is recommended that the village management committees be fully supported by Namibia's MFMR and that the fishery be controlled by the local communities, with illegal immigrants excluded (or better regulated by the Namibian authorities if there should be spare fishing capacity once all Namibian fishers have been accommodated).

The fishery should be aimed at the large cichlid species as in the 1970s and in the most recent inundation (Peel et al., 2015b; Peel, 2017; Taylor, 2017), as these yield the most valuable returns. The fishery used nets with mesh sizes large enough to allow most of the valuable large cichlids to reach maturity before entering the fishery. There may, however, be scope for a small meshed floating gillnet fishery for *B. lateralis* if this species again becomes abundant in the lake in its next inundation (Peel et al., 2015a).

Upper Zambezi floodplain fisheries

In contrast to Lake Liambezi, the fisheries of both the Central Barotse Floodplain and Zambezi/Chobe floodplains underwent catastrophic economic collapse from 2010 following a change from using multifilament gillnets to nets made of monofilament (Tweddle et al., 2015). Collapse of the stocks of the valuable large cichlids was compounded by the use of fine-meshed dragnets.

The fisheries are grossly overfished and until now have effectively been unmanaged. The Zambezi-/Chobe floodplain fishery is transboundary between Namibia and Zambia, which complicates efforts to develop community management structures. Establishing effective fisheries management is therefore difficult, but there are encouraging developments taking place on both sides of the border, incorporating the results and recommendations from the SASSCAL and other associated NNF projects.

Management recommendations have been made to MFMR based on the research results, and the key recommendations have been implemented. These are (1) the establishment of a network of Fish Protection Areas (FPAs), (2) a ban on the use of monofilament nets, and (3) the establishment of a harmonised closed season between Namibia and Zambia.

In Namibia, increasing areas of the river and floodplains now fall under conservancies, where the communities have recognised rights over the management of natural resources. These community bodies are the focus of community management initiatives.

(A) Fish Protection Areas: The concept of community-based Fish Protection Areas (FPAs) where no fishing is allowed has been accepted by the floodplain conservancies, and pilot FPAs have been proposed and established by conservancies, recognised by Traditional Authorities, and gazetted by MFMR (2015). The Sikunga Channel FPA in particular is successful, with conservancy-appointed fish guards supported by private enterprise and conducting daily patrols. Their activities are covered by a Facebook page, 'Sikunga Fish Guards'.

(B) Ban on monofilament nets: A ban on the use of monofilament nets was gazetted in December 2016.

(C) Closed season: An annual closed season for the Namibia section of the Upper Zambezi and the Chobe Rivers and floodplain is now gazetted for the period from December 1 to the end of February, in harmony with that on the Zambian side of the river.

These measures should allow for improvement in the fisheries, but other recommendations need to be enacted. Recognition of conservancies is needed in the revision of the Fisheries Act that is currently in progress, to enable greater participation by conservancies in management. MFMR is recognising the conservancies, as shown by its gazetting of the FPAs, but the relationship needs to be formally strengthened. There needs to be more scope for the establishment of local by-laws, as the fisheries are highly diverse and dynamic, meaning that standardised regulations are not appropriate in some fishery areas. Recognised community organisations such as conservancies and community fisheries management committees need to have formal avenues through which by-laws can be agreed on and implemented.

Climate change impacts on Zambezi fisheries

The Zambezian riverine, floodplain, and lake fisheries are of immense value to the riparian communities, both economically and, much more importantly, for food security. In this chapter we have highlighted the high economic value of the Lake Liambezi fishery and shown how climate variability has a major impact on livelihoods. Under projected climate change scenarios for this region (e.g., Midgley et al., 2005; Turpie et al., 2010), rainfall is expected to decrease in the catchments of these rivers. This will not only reduce river flow volumes and thus potential fish production but will also expose fish populations to ever greater fishing pressure, exacerbating an already serious overfishing situation in the region. The risks from potential climate change therefore highlights the need for much greater emphasis on the management of the fisheries, with a major emphasis on community empowerment to learn the lessons from the Lake Liambezi fishery and apply these to the Zambezi as a whole. A major predicted consequence of global climate change is increased variability in the magnitude and duration of flood events. Developing proactive management approaches that allow for the maximisation of harvests from ephemeral water bodies such as Lake Liambezi when these are available, while mitigating against excessive exploitation in the perennial rivers during dry periods, will be a major challenge in the future.

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References

Bell-Cross, G. (1974) A fisheries survey of the Upper Zambezi River system. *Occasional Papers of the National Museums and Monuments of Rhodesia. Series B, Natural Sciences*, **5**, 279–338.

Duerre, D. (1969) Fishery development in the Central Barotse Floodplain: report to the government of Zambia. FAO, Rome.

Grobler, M. & Ferreira, J. (1990) The dying of Lake Liambezi. *Custos* **19**, 39–47.

Halls, A.S. (1998) *An assessment of the impact of hydraulic engineering on floodplain fisheries and species assemblages in Bangladesh*. MSc thesis, Imperial College of Science, Technology and Medicine, London.

Hay, C.J. & van der Waal, B.C.W. (2009) *Analysis of historic fisheries research data for the Caprivi Region, April 2009*. Integrated management of Zambezi/Chobe River System — transboundary fishery resource, Namibia/ Zambia/Botswana, Technical Report no. MFMR/NNF/WWF/ Phase I/2.

Kelley, D.W. (1968) Fishery development in the Central Barotse Floodplain: report to the government of Zambia. FAO, Rome.

Lae, R. (1992) Influence de l'hydrobiologie sur l'évolution des pêcheries du delta Centrale du Niger, de 1966 à 1989. *Aquatic Living Resources,* **5**, 115–126.

MFMR (2003) Inland Fisheries Resources Act, 2003. Namibia Government Gazette, 23 April 2003, no. 2963.

MFMR (2015) Declaration of Sikunga Channel and Kasaya Channel as fisheries reserves: Inland Fisheries Resources Act, 2003. Namibia Government Gazette, 25 November 2015, no. 5882.

Midgley, G., Hughes, G., Thuiller, W., Drew G. & Foden, W. (2005) *Assessment of potential climate change impacts on Namibia's floristic diversity, ecosystem structure and function*. Climate Change Research Group, SANBI, Cape Town, RSA, for Namibian National Biodiversity Programme, Windhoek, Namibia.

Murphy, C. (2017) *A socio-economic description of the Lake Liambezi Fisheries Zambezi Region, Namibia (with emphasis on the latest inundation 2009 to 2016)*. NNF/SASSCAL Project Report, 39 pp.

Peel, R.A., Tweddle, D., Chilala, A., Murphy, C., Chinyawezi, K., Kalauka, R. & Weyl, O.L.F. (2013) *Ecological and socio-economic baseline assessment of artisanal fishing in the Greater Liuwa Ecosystem, Western Zambia*. African Parks Zambia, Liuwa Plain National Park, Zambia.

Peel, R., Taylor, G., Tweddle, D. & Weyl, O. (2014) An assessment of the fish and fishery of the Barotse Floodplain, Upper Zambezi River, Zambia. NNF/SASSCAL Project Report, 14 pp.

Peel, R.A., Taylor, G.C., Hay, C.J., Tweddle, D. & Weyl, O.L.F. (2015a) Assessment of offshore fisheries dynamics in Lake Liambezi: potential for development of an offshore fishery. GoGreen/NNF, Namibia.

Peel, R.A., Tweddle, D., Simasiku, E.K., Martin, G.D., Lubanda, J., Hay, C.J. & Weyl, O.L.F. (2015b) Ecology, fish and fishery of Lake Liambezi, a recently refilled floodplain lake in the Zambezi Region, Namibia. *African Journal of Aquatic Science*, **40**, 417–424.

Peel, R.A. (2017) *Colonisation and succession of fishes in Lake Liambezi, a shallow ephemeral floodplain lake in southern Africa*. Unpublished PhD thesis, Rhodes University, Grahamstown, RSA.

Seaman, M.T., Scott, W.E., Walmsley, R.D., van der Waal, B.C.W. & Toerien, D.F. (1978) A limnological investigation of Lake Liambezi, Caprivi. *Journal of the Limnological Society of Southern Africa,* **4**, 129–144.

Taylor, G.C. (2017) *Comparative fish ecology in three periodically connected rivers in the Upper Zambezi and Okavango ecoregions*. Unpublished PhD thesis, Rhodes University, Grahamstown, RSA.

Turpie, J., Midgley, G., Brown, C, Barnes, J., Pallett, J., Desmet, P., Tarr, J. & Tarr, P. (2010) *Climate change vulnerability and adaptation assessment for Namibia's biodiversity and protected area system*. Ministry of Environment and Tourism, Directorate of Parks & Wildlife Management, Windhoek, Namibia.

Tweddle, D. (2010) Overview of the Zambezi River System: its history, fish fauna, fisheries, and conservation. *Aquatic Ecosystem Health and Management*, **13**, 224–240.

Tweddle, D. (2015) What factors drive fishery yields in the Lower Shire River, Malawi? *African Journal of Aquatic Science*, **40**, 307–310.

Tweddle, D., Cowx, I.G., Peel, R.A. & Weyl, O.L.F. (2015) Challenges in fisheries management in the Zambezi, one of the great rivers of Africa. *Fisheries Management and Ecology*, **22**, 99–111.

Tweddle, D., Hay, C., Peel, R. & Weyl, O. (2012) Lake Liambezi, Namibia: fishing community assumes management responsibility. E-Poster, 6th World Fisheries Congress, Edinburgh, Scotland.

Tweddle, D., Skelton, P.H., van der Waal, B.C.W., Bills, I.R., Chilala, A. & Lekoko, O.T. (2004) *Aquatic biodiversity survey for the 'Four Corners' Transboundary Natural Resources Management Area. Final Report – July 2004.* SAIAB Investigational Report 71. African Wildlife Foundation, Kasane, Botswana.

Tweddle, D., Weyl, O.L.F., Hay, C.J., Peel, R.A. & Shapumba, N. (2011) Lake Liambezi, Namibia: fishing community assumes management responsibility, July 2011. Field document no. MFMR/NNF/WWF/Phase II/4.

van der Waal, B.C.W. (1980) Aspects of the fisheries of Lake Liambezi, Caprivi. *Journal of the Limnological Society of Southern Africa*, **6**, 19–31.

Weiss, G. (1970) *Fishery development in the Central Barotse Floodplain: report to the government of Zambia.* Rome, FAO.

Welcomme, R.L. (1978) Some factors affecting the catch of tropical river fisheries. *Symposium on river and floodplain fisheries in Africa. Bujumbura, Burundi, 21–23 November 1977* (ed. by R.L. Welcomme), pp. 266–277. CIFA Technical Paper no. 5. FAO, Rome.

Welcomme, R.L. (1985) *River fisheries.* FAO Fisheries Technical Paper 262. FAO, Rome.

Welcomme, R.L. (2001) *Inland fisheries: ecology and management.* FAO, Rome and Fishing News Books, Oxford.

Welcomme, R.L. & Hagborg, D. (1977) Towards a model of a floodplain fish population and its fishery. *Environmental Biology of Fishes*, **2**, 7–24.

Winemiller, K.O. (1991) Comparative ecology of *Serranochromis* species (Teleostei: Cichlidae) in the Upper Zambezi River floodplain. *Journal of Fish Biology*, **39**, 617–639.

Winemiller, K.O. & Kelso-Winemiller, L.C. (1994) Comparative ecology of the African pike, *Hepsetus odoe*, and tigerfish, *Hydrocynus forskahlii*, in the Zambezi River floodplain. *Journal of Fish Biology*, **45**, 211–225.

Winemiller, K.O. & Kelso-Winemiller, L.C. (1996) Comparative ecology of catfishes of the Upper Zambezi River floodplain. *Journal of Fish Biology*, **49**, 1043–1061.

References [CrossRef]

Bell-Cross, G. (1974) A fisheries survey of the Upper Zambezi River system. *Occasional Papers of the National Museums and Monuments of Rhodesia. Series B, Natural Sciences*, **5**, 279–338.

Duerre, D. (1969) Fishery development in the Central Barotse Floodplain: report to the government of Zambia. FAO, Rome.

Grobler, M. & Ferreira, J. (1990) The dying of Lake Liambezi. *Custos* **19**, 39–47.

Halls, A.S. (1998) *An assessment of the impact of hydraulic engineering on floodplain fisheries and species assemblages in Bangladesh*. MSc thesis, Imperial College of Science, Technology and Medicine, London.

Hay, C.J. & van der Waal, B.C.W. (2009) *Analysis of historic fisheries research data for the Caprivi Region, April 2009*. Integrated management of Zambezi/Chobe River System — transboundary fishery resource, Namibia/Zambia/Botswana, Technical Report no. MFMR/NNF/WWF/ Phase I/2.

Kelley, D.W. (1968) Fishery development in the Central Barotse Floodplain: report to the government of Zambia. FAO, Rome.

Lae, R. (1992) Influence de l'hydrobiologie sur l'évolution des pêcheries du delta Centrale du Niger, de 1966 à 1989. *Aquatic Living Resources*, **5**, 115–126. CrossRef

MFMR (2003) Inland Fisheries Resources Act, 2003. Namibia Government Gazette, 23 April 2003, no. 2963.

MFMR (2015) Declaration of Sikunga Channel and Kasaya Channel as fisheries reserves: Inland Fisheries Resources Act, 2003. Namibia Government Gazette, 25 November 2015, no. 5882.

Midgley, G., Hughes, G., Thuiller, W., Drew G. & Foden, W. (2005) *Assessment of potential climate change impacts on Namibia's floristic diversity, ecosystem structure and function*. Climate Change Research Group, SANBI, Cape Town, RSA, for Namibian National Biodiversity Programme, Windhoek, Namibia.

Murphy, C. (2017) *A socio-economic description of the Lake Liambezi Fisheries Zambezi Region, Namibia (with emphasis on the latest inundation 2009 to 2016)*. NNF/SASSCAL Project Report, 39 pp.

Peel, R.A., Tweddle, D., Chilala, A., Murphy, C., Chinyawezi, K., Kalauka, R. & Weyl, O.L.F. (2013) *Ecological and socio-economic baseline assessment of artisanal fishing in the Greater Liuwa Ecosystem, Western Zambia*. African Parks Zambia, Liuwa Plain National Park, Zambia.

Peel, R., Taylor, G., Tweddle, D. & Weyl, O. (2014) *An assessment of the fish and fishery of the Barotse Floodplain, Upper Zambezi River, Zambia*. NNF/SASSCAL.

Peel, R.A., Taylor, G.C., Hay, C.J., Tweddle, D. & Weyl, O.L.F. (2015a) Assessment of offshore fisheries dynamics in Lake Liambezi: potential for development of an offshore fishery. GoGreen/NNF, Namibia.

Peel, R.A., Tweddle, D., Simasiku, E.K., Martin, G.D., Lubanda, J., Hay, C.J. & Weyl, O.L.F. (2015b) Ecology, fish and fishery of Lake Liambezi, a recently refilled floodplain lake in the Zambezi Region, Namibia. *African Journal of Aquatic Science*, **40**, 417–424. CrossRef

Peel, R.A. (2017) *Colonisation and succession of fishes in Lake Liambezi, a shallow ephemeral floodplain lake in southern Africa*. Unpublished PhD thesis, Rhodes University, Grahamstown, RSA.

Seaman, M.T., Scott, W.E., Walmsley, R.D., van der Waal, B.C.W. & Toerien, D.F. (1978) A limnological investigation of Lake Liambezi, Caprivi. *Journal of the Limnological Society of Southern Africa*, **4**, 129–144. CrossRef

Taylor, G.C. (2017) *Comparative fish ecology in three periodically connected rivers in the Upper Zambezi and Okavango ecoregions*. Unpublished PhD thesis, Rhodes University, Grahamstown, RSA.

Turpie, J., Midgley, G., Brown, C, Barnes, J., Pallett, J., Desmet, P., Tarr, J. & Tarr, P. (2010) *Climate change vulnerability and adaptation assessment for Namibia's biodiversity and protected area system.* Ministry of Environment and Tourism, Directorate of Parks & Wildlife Management, Windhoek, Namibia.

Tweddle, D. (2010) Overview of the Zambezi River System: its history, fish fauna, fisheries, and conservation. *Aquatic Ecosystem Health and Management*, **13**, 224–240. CrossRef

Tweddle, D. (2015) What factors drive fishery yields in the Lower Shire River, Malawi? *African Journal of Aquatic Science*, **40**, 307–310. CrossRef

Tweddle, D., Cowx, I.G., Peel, R.A. & Weyl, O.L.F. (2015) Challenges in fisheries management in the Zambezi, one of the great rivers of Africa. *Fisheries Management and Ecology*, **22**, 99–111. CrossRef

Tweddle, D., Hay, C., Peel, R. & Weyl, O. (2012) Lake Liambezi, Namibia: fishing community assumes management responsibility. E-Poster, 6th World Fisheries Congress, Edinburgh, Scotland.

Tweddle, D., Skelton, P.H., van der Waal, B.C.W., Bills, I.R., Chilala, A. & Lekoko, O.T. (2004) *Aquatic biodiversity survey for the 'Four Corners' Transboundary Natural Resources Management Area. Final Report – July 2004*. SAIAB Investigational Report 71. African Wildlife Foundation, Kasane, Botswana.

Tweddle, D., Weyl, O.L.F., Hay, C.J., Peel, R.A. & Shapumba, N. (2011) Lake Liambezi, Namibia: fishing community assumes management responsibility, July 2011. Field document no. MFMR/NNF/WWF/Phase II/4.

van der Waal, B.C.W. (1980) Aspects of the fisheries of Lake Liambezi, Caprivi. *Journal of the Limnological Society of Southern Africa*, **6**, 19–31. CrossRef

Weiss, G. (1970) *Fishery development in the Central Barotse Floodplain: report to the government of Zambia.* Rome, FAO.

Welcomme, R.L. (1978) Some factors affecting the catch of tropical river fisheries. *Symposium on river and floodplain fisheries in Africa. Bujumbura, Burundi, 21–23 November 1977* (ed. by R.L. Welcomme), pp. 266–277. CIFA Technical Paper no. 5. FAO, Rome.

Welcomme, R.L. (1985) *River fisheries.* FAO Fisheries Technical Paper 262. FAO, Rome.

Welcomme, R.L. (2001) *Inland fisheries: ecology and management.* FAO, Rome and Fishing News Books, Oxford. CrossRef

Welcomme, R.L. & Hagborg, D. (1977) Towards a model of a floodplain fish population and its fishery. *Environmental Biology of Fishes*, **2**, 7–24. CrossRef

Winemiller, K.O. (1991) Comparative ecology of *Serranochromis* species (Teleostei: Cichlidae) in the Upper Zambezi River floodplain. *Journal of Fish Biology*, **39**, 617–639. CrossRef

Winemiller, K.O. & Kelso-Winemiller, L.C. (1994) Comparative ecology of the African pike, *Hepsetus odoe*, and tigerfish, *Hydrocynus forskahlii*, in the Zambezi River floodplain. *Journal of Fish Biology*, **45**, 211–225. CrossRef

Winemiller, K.O. & Kelso-Winemiller, L.C. (1996) Comparative ecology of catfishes of the Upper Zambezi River floodplain. *Journal of Fish Biology*, **49**, 1043–1061. CrossRef