UNIVERSITY OF BOTSWANA

BOTSWANA UNIVERSITY OF AGRICULTURE AND NATURAL RESOURCES

EFFECT OF SOIL WATER DEFICIT ON WATER USE EFFICIENCY OF COWPEA (*Vigna unguiculata L. Walp*)

A dissertation submitted in partial fulfillment of the requirements for the award of the Master of Science Degree in Crop Science (Agronomy)

By

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DEPARTMENT OF CROP SCIENCE AND PRODUCTION

DECLARATION

I solemnly declare that this thesis is my original work except where otherwise indicated and has not been submitted for any award for a degree at any other university.

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Chipo Nkomazana

August 2016

APPROVAL

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Head of Department’s name	Date	Signature
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DEDICATION

This work is dedicated to my husband for his support and encouragement during the challenges of graduate school and life. To my parents who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve. I am very thankful for having you in my life.

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To God be the glory.

ABSTRACT

There is a global concern over the capacity to feed a rapidly growing world population against a background of climate change which challenges productivity of major crops such as cowpea and their ability to ensure food security in the future. Cowpea in Botswana is widely grown in the Kalahari Desert and the hardveld in the Eastern region where it is exposed to drought stress during development due to low and uneven rainfall. Such conditions require crops which can efficiently make use of the available water.

A field study was conducted from December 2014 to May 2015 at the Botswana University of Agriculture and Natural Resources, Sebele to determine the effect of soil water deficit on water use efficiency and its association with plant morphology and grain yield in cowpea. The experimental design was a randomized complete block design (RCBD) with two treatment factors: water (irrigated and rainfed) and six cowpea genotypes, replicated four times. The six genotypes were also evaluated for rainfall use efficiency (RUE) in the Kalahari Desert-Hukuntsi under a randomized complete block design (RCBD) with four replications. Data was collected on plant height, stem diameter, canopy spread, days to flowering and maturity, leaf area, leaf area index, specific leaf area (SLA) and plant water status; relative water content (RWC) and percent plant survival. Grain yield (GY) and its components (number of pods per plants, pod length, number of seeds per pod, 100 seed weight, harvest index, biomass) as well as water use (WU) and water use efficiency (WUE) were evaluated at harvest. However, WUE was also determined at anthesis.

Water deficit treatment reduced the mean WU by 80% causing significant ($P<0.0001$) reductions in biomass and grain yield. Reductions in above ground biomass and grain yield were due to a decline in leaf area and its related traits as well as yield components, while high RWC of leaves was maintained in some genotypes which had more survival. Cowpea genotypes varied significantly on WUE; rainfed genotypes were more efficient than the irrigated types both in above ground biomass and grain yield WUE. The results showed that at flowering, WUE was high and decreased with maturity. At maturity WUE ranged from 0.43 to 3.15 kg $ha^{-1}mm^{-1}$ and 1.65 to 17.32 kg $ha^{-1}mm^{-1}$ for grain yield and above ground biomass respectively. RUE values were also higher than WUE under rainfed conditions. BCA 001 and BCA 019 were the most water use and rainfall use efficient genotypes in terms of grain production while for above ground biomass, BCA 009 was the most efficient. The strong and significant correlations between WU and RWC with WUE indicate that high WUE was largely due to lower water use and maintenance of plant water status as opposed to yield gain. Crops selected for higher WUE under water deficit conditions should therefore have lower water use and be able to maintain yield.

Key Words: Grain yield, biomass, relative water content, water deficit, water use, water use efficiency.

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ACRONYMS

AGB	Above Ground Biomass
BUAN	Botswana University of Agriculture and Natural Resources
CEC	Carbon Exchange Capacity
CHI	Crop Harvest Index
DW	Dry Weight
EC	Electrical Conductivity
ET	Evapotranspiration
FAO	Food and Agricultural Organisation
FAOSTAT	Food and Agricultural Organisation Statistics
FW	Fresh Weight
GA	Ground Area
GY	Grain Yield
I	Irrigated
IPCC	Intergovernmental Panel on Climate Change
ISPAAD	Integrated Support Programme for Arable Agriculture Development
IWUE	Instantaneous Water Use Efficiency
LA	Leaf Area
LAI	Leaf Area Index
LSD	Least Significant Difference
MoA	Ministry of Agriculture

NPGRC	National Plant Genetic Resources Centre
P	Precipitation
PHI	Pod Harvest Index
R	Rainfed
RUE	Rainfall Use Efficiency
RWC	Relative Water Content
SAS	Statistical Analysis Software
SLA	Specific Leaf Area
TE	Transpiration Efficiency
TP	Total precipitation
TW	Turgid Weight
WU	Water Use
WUE	Water Use Efficiency
WUEa	Anthesis Water Use Efficiency
WUEgy	Grain yield Water Use Efficiency
WUEagb	Above Ground Biomass Water Use Efficiency

CHAPTER ONE

INTRODUCTION

1.1 General introduction

Cowpea (*Vigna unguiculata* (L) Walp.) is one of the most important food legume in the arid and semi-arid regions of the tropics and subtropics where water stress is a major production constraint due to low and erratic rainfall (Ahmed and Suliman, 2010; Pungulani, 2014).

The Food and Agriculture Organisation (FAO) estimated that 90% of the world cowpea production of 5.7 million tonnes is produced on about 10 million hectares in Africa (FAOSTAT, 2010). West Africa is the key cowpea producing zone and countries like Nigeria, Niger, Senegal, Ghana, Mali and Burkina Faso take the lead (FAOSTAT, 2010). In Botswana cowpea production is rainfed; the latest Agricultural Census Report (CSO, 2013) indicated that cowpea which is categorized as a pulse is among the most cultivated crops after maize and sorghum having recorded 10% of 2012 production (Figure 1.1). Production is more dominant in the Eastern part of the country. In the past ten years an average of 2640.7 tonnes was produced from 24300 ha planted area with an average yield of 154kg/ha. The census data (2011 and 2012) indicated a significant drop in production countrywide; production went down tremendously from 4700 tonnes to 2285 tonnes giving a yield of 133kg/ha and 63kg/ha in 2011 and 2012 respectively. Erratic rainfalls have been pointed out as one of the major causes of losses in grain production (MoA, 2010).

Generally production in Botswana is low as compared to countries such as Nigeria and Niger which are lead producers of cowpeas. In 2012 Nigeria and Niger had production and yield of 2 500 000 tonnes (7813 kg/ha), 1329514 tonnes (2828kg/ha) respectively, (FAOSTAT, 2013). Several factors account for high yield in West Africa; a number of varieties have been developed combining diverse plant type and different maturity periods, resistance to several diseases, insect pests and parasitic weeds, and possessing other good agronomic traits (Singh *et al*., 1997).

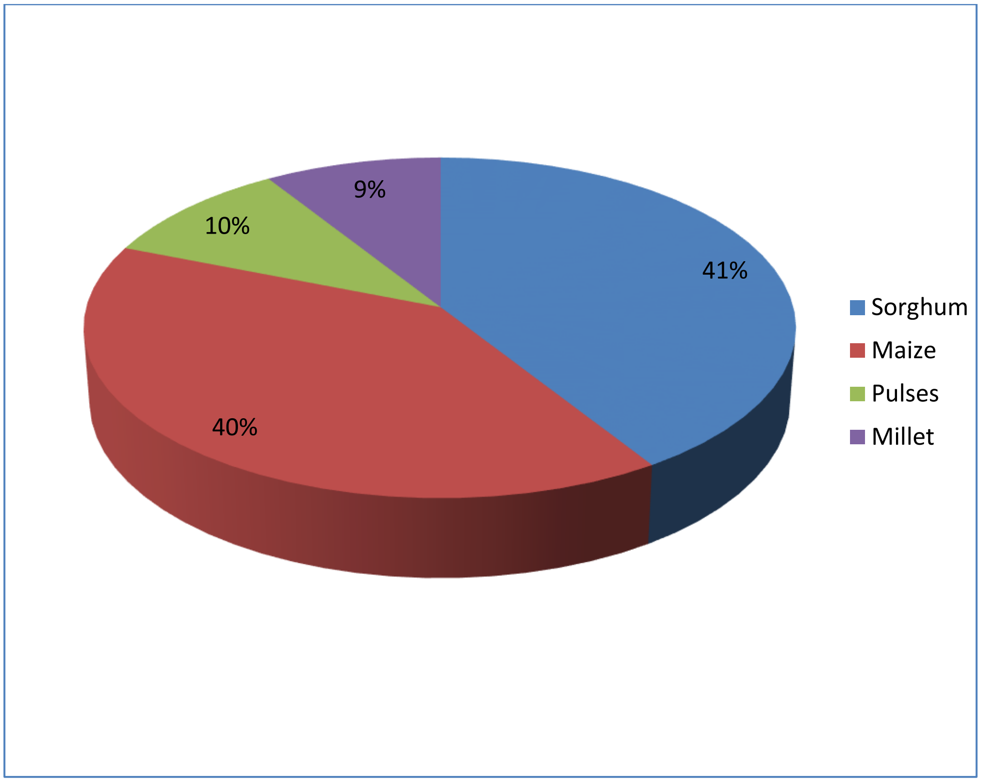


Figure 1.1: 2012 percent production by crop in Botswana, CSO (2013)

1.2 Justification of study

Issues surrounding water scarcity have become topical as water is becoming more limited. Climate change forecast has predicted increased occurrence and severity of droughts for Sub Saharan Africa, a situation that will increase the risk of crop failure (IPCC, 2007). The frequency of drought in Botswana has been increasing over the past few years, from once every four years to once every two years (MoA, 2010). Currently, the country is experiencing the worst drought in thirty years with heat waves in the midst of acute water shortages. Grain production is dominated by rainfed agriculture hence the frequency of drought makes production low and unreliable (MoA, 2010).

Hopes for food security are dashed and the country risks a reversal of millennium development goals attainment.

Cowpea is known to perform well under water stressed conditions with an ability to efficiently use the available resources (Singh *et al*., 1997). Though drought resistant, productivity in many cowpea cultivars is negatively affected by prolonged droughts and high temperatures (Hall, 2012) and recently is partly attributed to the effect of climate change (Pungulani, 2014). Increasing water use efficiency of a variety has shown to be advantageous in growing conditions where there is limited water availability. However, it is not well established if higher water use efficiency can lead to higher biomass, hence it is important to determine whether or not increased water use efficiency is a beneficial trait for cowpea. Most research on water use efficiency of cowpea has been conducted under controlled environment. The results of those experiments require confirmation under natural environmental conditions.

The government of Botswana has introduced programmes such as the Integrated Support Programme for Arable Agriculture Development (ISPAAD) to address the challenges facing rain-fed agriculture. Some of the aims of the programme are to improve food security, provision of free inputs (seeds and fertilizers) as well as increasing grain production. However, this programme does not have targets for assessing or alleviating the vulnerability of agriculture to climate change therefore crop production is still a risk. In that context, the unpredictability of future climate change coupled with water scarcity has necessitated the need to study water use efficiency of cowpea in Botswana. There is no documented evidence of water use efficiency study on cowpea in the country hence it is important to identify water use efficient cowpea genotypes. The knowledge of crop water requirements according to Blum (2005) is crucial to produce crops better adapted to the challenging environment and with a low demand for water. Due to variation in growth and development among cowpea genotypes, it is also necessary to study crop variation in relation to WUE (Ericson *et al.*, 2012).

The identified water use efficient genotypes when adopted by farmers could assist in enhancing sustainable cowpea production, improve food security and alleviate poverty among resource poor farmers. Knowledge of biomass production per unit cropped area per unit of water consumed provides an excellent tool for genotypic evaluation under water limited conditions and under specific locations (Munoz-Perea *et al.,* 2007). The identified water use efficient genotypes in this study will be recommended for further development Department of Agricultural Research (Ministry of Agriculture, Botswana) for breeding.

1.3 Objectives

1.3.1 General objective

This study was conducted to determine the effect of soil water deficit on water use efficiency of cowpea genotypes under irrigated and rainfed conditions.

1.3.1.1 Specific objectives

1. To evaluate water use efficiency of cowpea genotypes at anthesis and maturity.
2. To identify water use efficient cowpea genotypes under field conditions.
3. To establish the relationship between water use efficiency and associated plant traits.

1.4 Hypothesis

Ho: Cowpea genotypes do not differ in patterns of water use efficiency.

Ha: Cowpea genotypes differ in patterns of water use efficiency.

CHAPTER TWO

LITERATURE REVIEW

2.1. The cowpea crop

Cowpea (*Vigna unguiculata* L. (Walp.) is a dicotyledonous plant belonging to the family Fabaceae and sub family Fabiodeae (Padulosi *et al.,* 1990). The centre of diversity of cowpea is found in West Africa, in an area encompassing the Savanna region of Nigeria, part of Burkina Faso and Northern Benin. The most primitive of the wild cowpea occurs in Namibia from the west, across Botswana, Zambia, Zimbabwe and Mozambique to the east, and the Republic of South Africa and Swaziland to the south (Singh *et al.,* 1997). India appears to be a secondary centre of diversity since genetic variability occurs there (Padulosi, 1997).

Cowpea can be grown under rainfed conditions and irrigation or residual soil moisture along river banks or lake flood plains during the dry season provided the temperature range is between 28^{o}C and 30^{o}C during the growing season. With the development of early maturing varieties, the crop can thrive in the Sahel zone, where the rainfall is less than 500 mm per annum (Dugje *et al.,* 2009). It is drought tolerant and well adapted to sandy and poor soils; being deep rooted, cowpea performs well in sandy soils to clay loam soils with pH range of 6-7 (Dadson *et al.,* 2003). Anthesis, flowering and grain filling are the most sensitive stages to drought (Adejare and Umebese, 2007). The occurrence of water stress during flowering is harmful to cowpeas with obvious reduction of yield which results in a decline in water use efficiency (Carvalho *et al*., 2000).

2.2. Uses of cowpea

Cowpea is one of the most important food crops, which guarantees food security and supplements the diet with protein in rural areas. It is the preferred pulse in large parts of Africa. The main use of cowpea as a food is as dry grains which has substantial quantities of protein (about 25%) and carbohydrates (about 64%), vitamins and fibre (Singh and Reddy, 2011). The seeds are most often harvested, dried and cooked whole or milled like a flour product and used in various recipes (Nielsen *et al.,* 1997). In Botswana and Zimbabwe boiled cowpea leaves are kneaded to a pulp and squeezed into small balls, which are dried and stored (Madamba *et al.,* 2006). In addition to human consumption, cowpea leaves and stems (stover) are also an important source of high quality hay for livestock feed (Abayomi and Abidoye, 2009).

Cowpeas intensify cropping systems by utilizing under-exploited production niches, serving as rotation and inter-crops. They fix atmospheric nitrogen which contributes to increased yields of nitrogen demanding crops grown after it (Jarma-Orozco *et al.,* 2013). Their fast growth not only improves soil-protective land cover, but also helps break pest, disease and weed cycles in cereal cropping systems. Certain cowpea lines can cause suicidal germination of the seeds of *Striga hermonthica*, which parasitizes pearl millet, sorghum and maize (Ahmed and Suliman, 2010). With regard to resource utilization, an intercrop of cowpea and maize utilizes water more efficiently than a monoculture of its species through exploring a larger total soil volume of water due to different rooting pattern (Ofori *et al.,* 2014).

2.3. Water availability as cowpea production constraint

The severity of drought is unpredictable as it depends on many factors such as occurrence and distribution of rainfall, evaporative demands and moisture storing capacity of soils (Abdulai, 2005). The African rainfed agriculture is viewed by many observers to be the most vulnerable sector to climate variability and a reduction of 50% in crop yields by 2020 in Sub Saharan Africa is predicted (IPCC, 2007). Spatial and temporal rainfall variability has been increasing in Southern Africa in recent years and as a result drought has become more intense and widespread. This has affected the production of rainfed crops such as cowpea as it limits biomass accumulation and consequently reduces grain yield hence is threatening food security in the region (Sithole and Murewi, 2009). As a result drought resistant crops are best suited for the region.

2.4 Drought resistance in cowpea

When the term “drought resistance” is applied to crops it means not only the ability to survive, but also to grow and yield satisfactorily under conditions where rainfall is insufficient (Xu-rong *et al.*, 2013). Drought resistance has been linked by O’Toole and Chang (1979) to the four plant response strategies (escape, tolerance, avoidance and recovery) in relation to drought. Drought avoidance involves strategies which help the plant maintain higher water status during periods of stress, either by efficient water absorption from roots or by reducing evapotranspiration from aerial parts (Manavalan *et al.,* 2009). Drought tolerance allows the plant to maintain turgor and continue metabolism even at low water potential either by protoplasmic tolerance or synthesis of osmo-protectants (Blum, 2005).

Cowpea employs two major types of drought tolerance; Type I and Type II (Mai-kodomi *et al*., 1999). For type I drought tolerance, plants stop growth after drought stress and maintain uniformity with a decline in turgidity in all tissues, including the uni-foliates and emerging tri-foliates. All plants parts gradually die. Type II drought tolerant lines remain green for a longer time and tri-foliates continue growing slowly in drought conditions under continued drought stress, tri-foliates of tolerant varieties wilt and finally die (Mai-kodomi *et al*., 1999). Therefore, to increase drought tolerance in cowpea two mechanisms are used; type I mechanism where the stomata close to reduce water loss through transpiration and cessation of shoot and leaves growth and type II, known as osmotic adjustment where there is continued slow growth (Boyer, 1996). Physiological traits for drought tolerance include high water use efficiency, maintenance of high leaf water potential, relative water content, specific leaf area and chlorophyll stability index (Songsri *et al.*, 2009). Other traits include delayed leaf senescence, root architecture and early maturity (Tuberosa, 2012). Among these traits, water use efficiency is very important for improving drought tolerance in cowpeas (Hall *et al*., 1997).

2.5 Water use efficiency and its contribution to drought tolerance

One of the most frequently used indices to evaluate the response of crops to a specific pedo-climatic condition and water supply is water use efficiency (Tanner and Sinclar, 1983). Water use by a crop is related to the total dry matter production or economic yield; hence the term WUE originates in the economic concept of productivity which measures the amount of a given resource that must be expended to produce a unit of an output (Taylor *et al.*, 1993). It is not the same as drought resistance, but rather refers to yield in relation to the water used to produce the yield (Hatfield, 2001).

Sinclair *et al*., (1984) defined water-use efficiency as a ratio of biomass accumulation, expressed as carbon dioxide assimilation, total crop biomass, or crop grain yield, to water consumed, expressed as transpiration, evapotranspiration, or total water input to the system. It is a ratio between two physiological (transpiration and photosynthesis) or agronomic (yield and crop water use) entities (Blum, 2005). The time scale for defining WUE can be instantaneous, daily or seasonal. According to Ogbonnaya *et al*., (2003) WUE measurements may be made using three techniques; in single leaf using gas exchange techniques, in whole plant and at canopy level based on evapotranspiration in the field and carbon isotope discrimination. Transpiration efficiency (TE), referred to as intrinsic water use efficiency can be evaluated at leaf level as the ratio of CO_2 exchange rate to transpiration (Morgan *et al*., 1993) or the ratio of marketable yield or biomass produced to transpiration (Hatfield *et al*., 2001). However, TE is difficult to monitor over long periods. For agronomic assessment, WUE has also been expressed as the rate of biomass produced to water consumed, referred to as biomass WUE. Biomass WUE is known to be relatively constant for a given crop under a given climate and the prevailing CO_2 concentration regardless of whether water supply is ample or deficient (Erickson *et al.*, 2012).

According to Hall *et al*., (1997) the use of the WUE trait in crop improvement programs is limited by the volume of work involved with its direct measurement especially on large number of lines under field conditions as well as lack of equipment to assess below ground biomass. Most research has therefore been directed to seeking surrogate traits that can provide a cheap and rapid measure of WUE (Ogbonnaya *et al*., 2003).

A major breakthrough came when Farquhar *et al.*, (1982) found that the extent to which C_3 plants discriminate against $\Delta\ ^{13}C$ during carbon assimilation was related to their WUE. Carbon isotope discrimination in C_3 plants is correlated with WUE because both processes are related to leaf internal CO_2 concentration. It has been shown that carbon isotope discrimination in C_3 plants is inversely related to the molar ratio of assimilation to transpiration (A/E), which is also termed instantaneous water use efficiency (IWUE). For cowpea, genotypic differences in $\Delta^{13}C$ have been described under field conditions (Hall *et al*., 1990, 1994). Unfortunately, both measurements in estimating WUE, ratio of CO_2 uptake to transpiration and carbon isotope discrimination had drawbacks (Hall *et al*., 1997). For the former gas exchange measurements have not been effective in detecting genotypic differences in cowpea while for the later the measurements were expensive in a large screening trial (Hall *et al*., 1997).

Specific leaf area (SLA) is another surrogate that has been investigated due to the independent associations of WUE and SLA with leaf photosynthetic capacity (Anyia and Herzog, 2004). High water use efficiency is related to biomass allocation pattern such that WUE increases with increasing leaf area per unit plant weight (Abdulai, 2005). Mechanisms such as reduced plant size, leaf area and leaf area index allow plants to reduce water use in order to avoid drought stress (Songsri *et al*., 2013). Several studies have reported a close association between SLA and genotypic variation in WUE of some species including peanut and sunflower, however in cowpea no such association has been reported (Araus *et al.,* 1997*).* A study by Ismail and Hall (1992) indicated highly significant genotypic differences in cowpea SLA, but they were not associated with differences in WUE. This is supported by Anyia and Herzog (2004) who reported that cowpea genotypic and drought induced variability in leaf area, leaf area ratio and SLA were interrelated but not closely associated with water use; no correlation between SLA and WUE was found.

2.5.1 Importance of water use efficiency

With the exception of soil fertility, no other environmental factor limits crop productivity more severely than water deficit. Hence, soil water utilization is an important limiting factor to crop production since it is essential for every growth and development phase starting from seed germination to maturation (Hall *et al.,* 1997). Sustainable and efficient use of water is of paramount importance for successful crop production (Ntombela, 2012). It is an important trait for improving drought tolerance in cowpeas; WUE would help save considerable amount of irrigation water. Further, an improvement in water use efficiency would significantly enhance total biomass production as well as yield at a given level of soil water availability (Hayatu and Mukhtar 2010). The estimation of WUE is also important for obtaining a useful crop parameter, especially for the crop growth models that estimate biomass accumulation from water use efficiency such as CropSyst (Stockle *et al*., 2003), Parch (Hess *et al*.,1997) and AquaCrop (Steduto *et al* ., 2009) models. Erickson *et al.,* (2012) observed that WUE might not provide much information about the competitive or yield advantage of one particular species over another because improved WUE may actually restrict growth. However, it is one trait that has been studied a great deal because it can give an idea of the variation amongst genotypes in ability where water is limited. This was demonstrated by Passioura (1994) when he defined yield as: the product of water transpired (WUE) and harvest index for a water limited environment.

2.5.2 Shoot and root traits related to WUE under drought

Under conditions of limited available soil water, the balance between the increase in water uptake by deeper roots and the reduction in water loss by stomatal control is critical in maintaining high crop productivity (Turner *et al.*, 2001). Stomatal conductance and root distribution in deeper soil are important physiological traits related to water use efficiency under drought conditions (Songsri *et al*., 2013). Crops can avoid drought conditions by increasing water uptake if sufficient water is available within the root zone (Taiz and Zeiger, 2006) and enhancing WUE by altering stomatal behavior (Passioura, 2002).

2.5.2.1 Shoot traits

Stomatal conductance is one of the major limitations to photosynthetic assimilation under drought conditions in cowpea (Singh and Raja, 2011). Stomatal response to leaf dehydration can vary widely across species. Cowpeas stomata are very sensitive to water stress hence the closure of the stomata is used by many genotypes to avoid dehydration (Ahmed and Suliman, 2010). This stomatal behavior regulates water loss and transpiration efficiency under drought stress and therefore influences WUE (Singh and Reddy, 2011). Stomatal closing is therefore the first line of defense against dehydration (Taiz and Zeiger, 2006). Plants that possess better control of stomatal function are more drought tolerant. Stomata can be regulated based on the level of water deficit by only partially closing, leading to some carbon fixation during drought conditions and an increase in the efficiency of water use (Songsri *et al.*, 2013). In drier environments, lower stomatal conductance results in yield gain and higher WUE (Condon *et al*., 2002). In contrast low stomatal conductance associated with more sensitive stomata to drought could result in considerable yield reductions as well as low WUE in favourable conditions (Manavalan *et al.*, 2009).

Studies conducted by Oliveria *et al.*, (2005) outlined stomatal conductance to be an indicator of water stress in cowpea and reported values of 0.03 and 0.18 mol H_20 m^{-2} $0s^{-1}$, the highest values indicating more tolerance to drought.

2.5.2.2 Root traits

Plants can adapt to drought by developing a longer taproot system which helps reach lower soil layers where water is available (Manavalan *et al.*, 2009). In addition, an extensive fibrous root system can be useful for foraging subsoil surface moisture and nutrients such as phosphorus (Liu *et al.*, 2005). According to Matsui and Singh (2003), drought tolerance mechanisms in legumes are closely related to the type of root system or root architecture and development. In some cultivars, better drought tolerance is associated with an increase in root dry matter per leaf area under mild water stress (Kumar *et al.*, 2012). A further strategy is a deeper penetration of roots into the soil to access soil moisture in deep soil layers better under more severe water stress. Varietal differences were found by Vadez *et al.*, (2015) in cowpea root architecture, with some varieties having a well spread deep root system while others concentrated roots in the upper soil level. The efficiency of soil water uptake by the root system is a key factor in determining the rate of transpiration and the varying strategies of adaptation to drought. Under conditions with limited available soil water, the balance between the increase in water uptake by deeper roots and the reduction in water loss by stomatal control is critical to maintaining high crop productivity (Cruz *et al*., 1992). Stomatal conductance and root distribution can therefore be used as selection criteria for drought tolerance in cowpeas.

2.5.3 Factors affecting water use efficiency

Water use efficiency of cowpea is a function of multiple factors that include physiological characteristics, genotype, weather conditions, agronomic practices as well as soil characteristics such as soil water holding capacity. Thus, to improve water use efficiency, integrated measures should be taken to optimize cultivar selection and agronomic practices to be adopted. Hence, factors affecting water use efficiency are categorized as climatic factors, plant, soil factors and crop management factors.

2.5.3.1 Climatic factors

Climate is the driving force of crop production and crop water use. Increasing air temperature and precipitation patterns influence crop yield and WUE (Kattge and Knorr, 2007). Factors like vapour pressure deficit, wind, high temperature and high irradiance may increase transpiration and therefore negatively affect WUE (Davies and Pereira, 1992). Crop water needs are higher when it is dry than when it is humid. Crops grown in different climatic zones will have different water needs and thus WUE varies accordingly (Ali *et al.*, 2012). High atmospheric humidity generally promotes higher WUE, on the other hand vapour pressure deficit increases exponentially with temperature; hence high temperature, and associated high vapour pressure deficit, would reduce biomass per unit transpiration and yield per unit seasonal evapotranspiration (Xu-rong *et al.*, 2013).

2.5.3.2 Plant factors

According to Vadez *et al.,* (2015) genotypic variation in crop response to drought depends on agronomic, environmental and genetic factors. High photosynthetic capacity, optimal plant density and adjusted plant architecture may increase water use efficiency because these factors may either increase the carbon assimilation or decrease water loss (Davies and Pereira, 1992). Traits that serve to conserve water (conservative traits) include low stomatal conductance, low leaf growth rate, or deep root systems provides better water use efficiency. They modify the evapotranspiration rate by affecting the resistance to water movement from soil to plant and from plant surface to the surrounding atmosphere (Yada, 2011).

Singh and Raja (2011) in their study stated stomatal conductance to be a major limitation to photosynthetic assimilation under drought conditions in cowpea; it is an important trait associated closely with WUE and the relationship between stomatal conductance and yield depends on water availability of whole growing period (Xu-rong, 2013). Under conditions of drought, a lower stomatal conductance results in increased wheat grain yield and higher water use efficiency (Xu-rong, 2013). Belko *et al.,* (2012) reported a decrease in stomatal conductance in cowpeas which resulted in a decrease in transpiration rate and increased WUE. Similar results have been found in pearl millet Kholova *et al.,* (2010) and chickpea Zaman-Allah *et al*., (2011).

The root is also an important genotypic trait affecting WUE. In cowpea, high root density, rooting depth and root dry matter per unit area are parameters that characterize the root system and are very important in WUE (Matsui and Singh, 2003). A higher density of deeply distributed roots allows for higher water absorption (Madamba *et al.,* 2006).

Under water deficit stress, leaf area is reduced due to a combination of leaf growth reduction and abscission; this reduces radiation interception and thus biomass production (Hayatu and Mukutar, 2010). However differences in canopy structure may affect WUE by affecting the amount of light intercepted and attenuated (Manavalan *et al.,* 2009). This is supported by Yada (2011); greater leaf area results in more rapid ground cover and reduced penetration of radiation energy to the soil surface for water evaporation.

2.5.3.3 Soil factors

Water requirement depends on both growth and transpiration and is related to environmental factors such as soil fertility (mineral nutrition) and soil moisture stress. Soil factors that affect water use efficiency include surface crusting, salinity, acidification, root distribution, soil depth, bulk density, texture and structure (Turner, 2004). Water use efficiency is determined by how well these factors are manipulated in order to maximize yield from every unit of available moisture (Hussein and Alva, 2014).

Changing the soil nutrient status also influences water use efficiency as a result of the nutrient status of the soil that influences plant growth and ultimately the amount of biomass produced per unit of water consumed. Application of fertilizers facilitates root growth which extracts soil moisture from deeper layers (Taiz and Zeiger, 2006). It is known that proper nutrient levels in the soil will lead to increased yields and a better water use efficiency (Yada, 2011). A study by Karikari *et al.,* (2001) indicated that legumes such as cowpeas have a high phosphorus requirement. This is because phosphorus stimulates root and plant growth, initiate nodule formation as well as improve the efficiency of rhizobium- legume symbiosis (Yuan *et al.,* 2011). Addition of Phosphorus and Potassium improved the water use efficiency of cowpeas under different water regimes (Zougmoré *et al*., 1998). Similar results were obtained by Hayat and Ali

(2012) who reported a 29% increase in grain WUE of mung and mash beans fertilized with phosphorus.

According to Alam *et al.,* (2014) tillage influences the physical properties of soil as well as the movement of water and nutrients in soil, hence their uptake by crops and their losses from soil-plant system. Tillage affects WUE by modifying the hydrological properties of the soil and influencing root growth and canopy development of crops (Nielsen *et al.,* 2005). Comparing four tillage systems (conventional, reduced, zero and manual tillage) Adekalu and Okunade (2006) concluded that reduced and conventional tillage systems produced higher yield and WUE in cowpea genotypes. Miriti *et al.,* (2012) reported higher water use efficiency and grain yield in maize under tied ridge tillage than under ox plough tillage.

2.5.3.4 Crop management factors

Management of soils and crops has a large influence on WUE, mainly because of its effects on the proportion of water transpired (Hatfield, 2001). The adoption of agronomic procedures such as minimum tillage, appropriate fertilizer use, improved weed/ disease/insect control, timely planting, and a range of rotation options, in conjunction with new cultivars, has the potential to increase the yields and rainfall use efficiency of dryland crops (Turner, 2004).

Plant health is governed by diseases, insects and weeds that compete for water and mineral resources hence it is important to manage pests. Weed control is an essential way of ensuring that the water stored in the soil is used by crops (Dwyer *et al.,* 1991). It is the most efficient means of reducing transpiration as they transpire more amounts of water compared to associated crop plants and this may increase WUE in crops, (Alam *et al.*, 2014). This is supported by Cooper *et al.,* (1987) who reported a double increase in WUE of soybean from 2.9-5.9kg ha^{1} mm^{-1}.

Crop rotations are important in WUE as they provide an opportunity to increase water use by a crop as roots of some crops have potential to penetrate deeper in the soil and this provides biopores for a subsequent crop (Turner, 2004). Legumes have been used in crop rotation with cereals and have given positive results on the yield and WUE. In an experiment by Hayati and Ali (2012) grain WUE of wheat was found to be 44% higher in plots which were previously under mung and mash beans as compared to non-legume “sorghum” plots.

High plant density increases crop-water use and reduces soil evaporation in Mediterranean-type environments, whereas low planting density and uneven planting can result in low yields and a greater proportion of small seeds resulting in poorer rainfall-use efficiency (Turner *et al*., 1994). However this contrasts with drought prone areas where low planting densities are frequently used to provide a greater source of water per plant and hence increased yields per plant (O’Connell *et al*., 2003).

Breeding and selecting crop cultivars that make more efficient use of water while maintaining productivity, crop quality and stable yields is also important in this ever increasing threat from water scarcity and erratic rainfall (Bhale and Wanajari, 2009). In addition, crop varieties of lower stomatal conductance which can generate higher yield by reducing their stomatal conductance during drought to reserve soil water have been recommended by Xu-rong *et al.*, (2013).

2.5.4 Methods of improving water use efficiency in crops

Improving water use efficiency is a twofold task that requires water be conserved by avoidance of waste and maximization of growth by using high yielding crop varieties, well adapted to local soils and climate.

Water use efficiency can be increased either by a decrease in stomatal conductance which causes a proportionately greater decrease in transpiration than photosynthesis, or by an increase in the intrinsic photosynthetic capacity hence the need for breeding cultivars with such traits (Xu-rong *et al.*, 2013). The identification of appropriate crops and cultivars with optimum physiology, morphology, and phenology to suit local environmental conditions, especially the pattern of water availability, is important within cropping systems management for improved WUE (Bhale and Wanjari, 2009).

There are several strategies to raising yield and water use efficiency in irrigated and rain-fed agriculture (Junlian, 2007). WUE may be improved by selection of crops and cropping systems based on available water supplies and increasing seasonal evapotranspiration (Patil, 2009). However, increasing seasonal evapotranspiration is practical in irrigated farming as it involves choosing the right efficient irrigation system and irrigation scheduling (Bennie & Hensley, 2001). Others increase WUE by increasing the total water supply to crops such as cultivation to improve infiltration, selecting varieties with deep roots and weed control (Condon *et al*., 2002). Among these strategies, breeding cultivars with high water use efficiency and drought tolerance is more practical and economical (Manavalan *et al.,* 2009).

2.15 Water use efficiency in cowpea

Crops differ in WUE largely due to high transpiration efficiency (TE) (Erickson *et al.,* 2012). In C4 plants, TE is twice higher than C3 plants; C4 plants like maize and sorghum yield more with less water with an average WUE of 35kg/mm water compared to averages of 20kg/mm water of C3 plants like cotton, peanut and cowpea (Patil, 2013).

Studies on WUE efficiency in several crops including cowpea have been done. Babalola (1980) reported a difference in WUE between three cowpea cultivars, the efficiency of the two low yielding cultivars being 1/3 and 1/5 of the top yielding one; WUE increased with increased soil water up to a certain limit. Mean grain water use efficiency of 0.52kg m^{-3} in cowpeas has been reported by Moroke *et al*. (2011).

Water use efficiency may increase as drought stress increases. A study by Anyia and Herzog (2004) indicated that water deficit improved WUE of two cowpea genotypes (IFH 27-8 and Lobia) by approximately 20%, but caused moderate to huge reductions in most genotypes. Water use efficiency of the two poorest cowpea genotypes (UCR 386 and RCXAC) as well as one of the best (Vita 7) under well-watered conditions were more or less stable under stress. However, the result for water use efficiency of cowpea genotypes by Hayatu and Mukhtar (2010) showed that genotypes exhibiting higher water use efficiency were recorded more at moderate stress conditions whereas at severe water stress, most of the genotypes recorded lower water use efficiency, except in one genotype. Similar results were previously reported by Calvache (1997) who reported mean WUE of 10kg ha^{-1} mm^{-1} under drought stress and 8.7 kg ha^{-1} mm^{-1} in moderate stress in common bean.

Genotypic variations in cowpeas and related species in terms of WUE exist. Vadez (2015) while comparing water use, transpiration efficiency and yield in cowpea and peanut concluded that cowpea required less water and was very efficient in water use than peanut. Likewise, genetic variation among peanut genotypes was reported by Songsri *et al.,* (2009); genotypes with large root systems maintained high WUE under drought and well watered conditions.

Water use efficiency also varies with the growth habit of plants. Hall (2004) showed that the erect cowpea cultivars maintained higher WUE under water stress conditions than the spreading types. Blum (2005) reported that genotypic variations in WUE are normally expressed mainly due to variations in water use (WU; the denominator). Reduced WU, which is reflected in higher WUE, is generally achieved by plant traits and environmental responses that reduce yield potential (YP). Improved WUE on the basis of reduced WU is expressed in improved yield under water-limited conditions only when there is need to balance crop water use against a limited and known soil moisture reserve. However, under most dry land situations where crops depend on unpredictable seasonal rainfall, the maximization of soil moisture use is a crucial component of drought resistance (avoidance), which is generally expressed in lower WUE (Allam *et al.*, 2014).

The genotypic and drought induced variability in leaf area, leaf area ratio and specific leaf area may be interrelated but not closely associated with cowpea biomass production or water use. Sometimes no correlation between these parameters and WUE is found (Anyia and Herzog, 2004). Ismail and Hall (1992) reported similar findings for cowpea, although some other studies have suggested a close relationship of specific leaf area with WUE or yield in wheat and cotton (Araus *et al*., 1997; Leidi *et al*., 1999).

In their experiment on water stress and water use efficiency in cowpea under controlled environment Razakou *et al.*, (2013) concluded that genotypic variations exist among cowpea genotypes for water use efficiency, due to their relatively low water use. Water stress significantly decreased biomass and water use efficiency of water-stressed cowpea varieties compared to the control, and the largest reduction was observed in the varieties TN5-78 for biomass (89%) and Nhyira for WUE (94%). The results also revealed that under water-stressed condition, varieties TN88-63 and Danilla with relatively low water use, significantly recorded highest values of biomass and water use efficiency. Biomass showed a significant strong positive correlation with water use efficiency. In general, WUE ranged from 13 to 34g/kg for the irrigated and 1 to 4g/kg for the water stressed varieties and the results suggested that greater biomass production under water stress was associated with low water use and high water use efficiency.

In other legume crops such as common bean, De Costa and Ariyawansha (1996) concluded that mean seasonal WUE for common bean under water stress was significantly higher than under well-watered conditions giving 4.025 and 3.532 g/kg for the water stressed and well watered conditions respectively. Each variety showed a significant increase in WUE under water deficit. Rao and Northup (2009) reported WUE for five forage crops (soybean, cowpea, mung bean, guar and pigeon pea) to range widely from year to year (12.9–26.3 kg ha^{-1} mm^{-1}) over the four years of the study, depending on growing season precipitation timing and amount. The forage WUE for the five crops was not different from one another and averaged 19.6 kg $ha^{-1}mm^{-1}$.

Shamsi *et al.* (2010) reported that cowpea grain yield increased more intensely as water utilization increased in the unit area resulting in an increase in WUE, a linear relationship of seasonal water use and total dry matter and grain yield was also found. Kiziloglu *et al*. (2009) similarly observed a linear relationship between water use efficiency and maize grain yield. They found that higher water deficiency resulted in a significant reduction in water use efficiency and maize yields.

Water use efficiency has also been studied by several authors in cowpeas and cereals intercropping system and most concluded that cowpeas were more efficient users of water grown as intercrops than as sole crops. Ofori *et al*. (2014) reported a WUE of 4.06kg $ha^{-1}mm^{-1}$ in cowpea sole cropping and a WUE of 13.24 kg $ha^{-1}mm^{-1}$ in cowpea maize intercrops.

Miriti *et al*. (2012) recorded grain WUE values ranging from 0.16–0.64, and 0.24–0.52 kg m^{-3} for maize/cowpea intercrop and single cowpea crop, respectively. The result shows that WUE was greatest under intercropping and least in single crop cowpea system. The greater WUE in intercrops is supported by Zhang *et al*. (2012) who stated that intercropping relationship provide a sound foundation for intensively utilizing resources temporally and spatially, and increase the crop yield per unit area greatly without increase of water consumption, so as to promote the crop water use efficiency effectively.

Different growth stages of cowpeas have shown to differ in terms of WUE. Water use efficiency increased with vegetative stage drought and was reduced by flowering stage and late season drought in an experiment by Turk and Hall (1980). However, a study by Ahmed and Suliman (2010) on the effect of water stress applied at different stages of growth on seed yield and WUE of cowpeas revealed that, the reproductive stage of development is the most sensitive to water deficit in cowpea, causing a reduction in WUE and seed yields of at least 50% in the 3 genotypes used. Hiler *et al*. (1972) found a high WUE at optimal water supply and at low deficit level during the vegetative stage of growth in cowpeas whereas Shouse *et al*. (1981) reported a high WUE for stress at the vegetative stage than stress at any other growth stage including optimum irrigation. However an exposure of several cultivars of cluster bean (*Cyamopsis tetragonoloba*) to water stress at the flowering, maturity and harvesting did not induce any significant variation in seed yield and WUE, whereas in common bean WUE was lowest with drought stress at flowering (Ahmed *et al.,* 2011, Calvache *et al.,* 1997).

Most literature indicates that high water use efficiency results in high grain yield under irrigated conditions. Some argue that under water stressed conditions higher water use efficiency results in more yield, hence WUE is important in water limited conditions. This however is due to low water use under water stressed condition since WUE is biomass per water use. Farmers eventually harvest grain yield, therefore higher water use efficient cowpea genotypes may be desirable if WUE is positively correlated to grain yield under water deficit conditions.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental site

Two field experiments were conducted during the 2015/16 growing season at the Botswana University of Agriculture and Natural Resources (BUAN) "Sebele" and in Hukuntsi. Sebele lies on latitude 24°33'S and longitude 25°54'E elevated at 993m above sea level with a semi-arid climate and an average rainfall (30 year mean) of 538mm (Legwaila *et al*., 2014). Hukuntsi is located on approximately 24°S and 22°E in the Kalahari sandveld and has an average elevation of 1,158m above sea level. The climate is classified as a subtropical desert (low latitude desert) (Totolo and Mosweu, 2012). The area is among the driest in the country with annual precipitation ranging between 250 and 350 mm and average annual temperature of 20.3 °C (Bhalotra, 1985).

Most rainfall received at the two sites starts in late October continuing to March/Apri). The agro-meteorological data as well as soil physical and chemical properties of the sites are presented in chapter four (Table 4.1 and Figure 4.1 and 4.2). Prior to the initiation of the experiments the experimental site in Sebele was managed under cowpea whereas Hukuntsi site was managed under maize and cowpea.

3.2 Selection of plant material

Genotypes selected for this research were obtained from the National Plant Genetic Resource Centre (NPGRC) in Sebele as released varieties by the Department of Agricultural Research (DAR) and landraces from local farmers. In total, eighty five (85) genotypes were grown for four months (06 February 2014 - 30 May 2014) at the BUAN agronomy field. Three seeds per hill were planted in rows of 20m, each row representing a genotype with 0.75m and 1m inter and intra row spacing respectively. The plant density used was 13 300 plants/ha. Selection and ranking of the six genotypes used on this experiment was based on data collected on days to anthesis, 50% maturity and grain yield. The scoring was done in such a way that the genotype with the lowest grain yield, more days to anthesis and 50% maturity was scored 85 until it got to the highest grain yield with few days to anthesis and maturity which was scored 1.The average rank for each genotype was then taken. The six selected genotypes are shown below.

Figure 3.1: External morphology of the seeds of six genotypes used for the experiments

3.3 Field trial layout

The experiment in Sebele was a Factorial arranged as a Randomized Complete Block Design (RCBD) with two factors; water and cowpea genotypes. There were two water regimes (irrigated and rainfed) and six cowpeas genotypes. Water regimes were assigned to blocks measuring 6m by 9.6m and replicated 4 times giving a total of four blocks for each level. Each block was split into six subplots measuring 2m by 4.8m to which the genotypes were assigned. To separate the irrigated and rainfed plots a 2m path was left and 0.75m used between blocks. In total there were 48 plots. In Hukuntsi the experiment was designed in a Randomized Complete Block Design (RCBD) with four replications and the six cowpea genotypes as a treatment. The experimental field was 200m by 36m occupying a total area of 7200m^2 (0.72ha), each plot measuring 50 m *6m.

Figure 2.2: Sebele experiment

Figure 3.3: Hukuntsi experiment

3.4 Agronomic practices

3.4.1 Land preparation

The land at the two sites was ploughed to a fine tilth with a disc plough followed by leveling. Prior to planting, soil samples were collected for determination of pH, exchangeable bases, organic carbon, texture, and available phosphorus by standard laboratory procedures. Sowing was done on the first week of December 2015 in Sebele followed by Hukuntsi on the third week. Seeds were sown at a rate of three seeds per hole and 0.75m spacing between holes and later thinned to one plant per hill giving a population of 17 857 plants/ha in.

3.4.2 Irrigation

Hukuntsi was managed under rainfed system while in Sebele, both trials (rainfed and irrigated) were established with irrigation to allow for maximum crop stand. Thereafter, irrigation was withdrawn in the rainfed trial to induce water deficit. Irrigation was delivered using a drip irrigation system. The irrigation system comprised of a 5000L water tank, mainline, sub mainlines and laterals. Dripper line spacing was based on inter row spacing (0.75m) and the average discharge rate per dripper was 8L/hr.

3.4.2.1 Irrigation scheduling and soil water measurement

A week after seedling emergence moisture access tubes made out of Polyvinyl chloride (PVC) 50 mm diameter were installed in each subplot at 3 depths; 10cm, 30cm and 60cm. Excluding those in the border, plants selected for access tubes were randomly selected ensuring that there are uniform. A distance of 5cm between the access tubes and plants was maintained in all the plots. Soil moisture monitoring was done weekly prior to irrigation with an ICT Moisture probe metre (MPM-160-B, ICT International Pty Ltd) commencing after installing access tubes continuing every week until crop maturity when plants were harvested for above ground biomass. Moisture probe readings (%) were converted to volumetric water content and profile soil water content depth S (m) calculated according to Evett *et al.* (1993) as;

$$S = \int_{O}^{Z} \theta(z)dz \qquad (1)$$

where θ(z) is soil water content (m^3 m^{-3}) at depth z

Z is the soil profile depth (m).

Irrigation amount was determined by calculating the difference between the field capacity and actual soil water content plus any rainfall recorded. Prior to planting and at harvesting in Sebele, gravimetric soil water content was taken in both irrigated and rainfed trials to determine the initial moisture content of the soil before the experiment was started and at the end. Soil samples were collected in the field at 10cm, 30 am and 60cm using an auger. After weighing the soil sample, it was placed in an oven at 105 ^{o}C for until the constant weight is obtained. After drying, the soil sample was weighed again. The gravimetric water content in fraction (Θv) was computed using equation 2 soil water content calculated with the formula below (Brady and Weil, 2008).

$$\theta v = \theta g * \rho b = \left[\frac{Mw - Ms}{Ms}\right] * [\rho b] \qquad (2)$$

where: θv = volumetric water content (mm)

θg = gravimetric water content (mm)

Mw is weight of wet soil sample (g)

Ms is weight of oven dry sample soil (g)

ρb = bulk density (g/cm^3).

To determine the bulk density, undisturbed soil samples of known volume were taken using a core sampler in the 0-10, 10-30 and 30-60 cm depths. The samples were oven dried at 105^{o}C to determine the dry weight fraction. Bulk density was then calculated as the ratio of dry weight of the soil to known cylindrical core sampler volume (Brady and Weil, 2008).

Figure 3.4: Irrigation layout in Sebele

Figure 3.5: Soil moisture measurements with a moisture probe meter.

3.4.2.2 Precipitation

Rainfall was recorded from rain gauges placed in the experimental sites and the recorded value were taken into account.

3.4.3 Pest control

Weed control was carried out by hand or hand hoeing while insect damage was visually monitored during the crop growing season. There was an outbreak of cowpea aphid "*Aphis craccivora* Koch" and chemical control was done using cypermethrin.

3.5 Plant response measurement

3.5.1 Vegetative development

The following indicators of plant growth were measured 55 days after planting to describe growth per plant: leaf number, plant height, leaf area, stem diameter and canopy spread. This was only done in Sebele. Three plants from each subplot were randomly selected and tagged for the measurements. Leaf number was counted only for fully unfolded leaves with at least 50% green leaf area.

Three leaves of each selected plant were sampled for leaf area, specific leaf area and leaf area index. Single leaf areas were measured using a leaf area meter (W C230 PCM) and averages taken and multiplied by the subsequent leaf number to get the total leaf area from the plants in which leaves were sampled from. This was followed by oven drying of the leaves at 72^{o}C for 24 hours to determine the leaf dry weight with a top pan balance (Adam AFP 4100L). Leaf area index (LAI) and specific leaf area (SLA) was calculated according to Gardner *et al.*, (1985) using equations 3 and 4.

$$LAI = LA / GA \tag{3}$$

$$SLA = LA / LW \tag{4}$$

where:

LA= Leaf area (m^2)

LW= Leaf weight (g)

GA= ground area (m^2)

Plant height was measured from the bottom of the plant up to the base of the 2nd youngest fully unfolded leaf using a meter ruler while canopy spread was determined by measuring the longest vine with a measuring tape. A venieer caliper was used to measure stem diameter.

3.5.2 Leaf relative water status determination

Relative water content was determined at the reproductive stage from tagged plants in each plot. The top-most fully expanded leaves were cut and immediately kept in small sealed plastic bags in an ice box. This was followed by weighing of the leaves with a top pan balance to obtain the fresh weight. The leaves were then soaked in distilled water for 24 hrs and blotted with paper towel to remove moisture on the leaves. The leaves were weighed to obtain the turgid weight and oven-dried at 80^{o}C for 24hrs. The dried leaves were then weighed and relative water content (RWC) calculated according to the formula proposed by (Barrs *et al.*, 1968);

$$RWC\ (\%) = [(FW-DW) / (TW-DW)] \times 100 \qquad (5)$$

where FW is the sample fresh weight, TW is the sample turgid weight and DW is the sample dry weight.

3.5.3 Phonological characters

The field was visited daily after seedling establishment to determine the number of days to 50% flowering and days to maturity.

3.5.4 Percent plant survival

Three rows in each subplot were selected and live and dead plants physically counted. Estimation of percent plant survival was done by calculating the ratio of live plants to the total number of plants in each row. This was only done in Hunkuntsi site.

3.6 Yield and yield components

In each experimental unit three plants were randomly selected and tagged to determine the following parameters:

3.6.1 Number of pods per plant

The total number of pods in the tagged plants was counted and the average number of pods per plant was determined.

3.6.2 Pod weight, length and number of seeds per pod

At maturity, pods from the tagged plants were harvested and a sample of ten pods was selected from each replication. Pod weight was determined using an electronic balance followed by measurement of pod length with a ruler. The number of seeds in each pod was then counted and the average number of seeds per pod determined.

3.6.3 100-Seed weight

100 seeds were counted from each sample which was used in determining pod weight and its associated parameters. Weighing of the seeds followed thereafter.

3.6.4 Grain yield

In each experimental unit, pods were harvested, dried and threshed and seed yield as kilograms per hectare “inclusive of seeds used in pod weight sampling” was determined for each genotype under different water regimes.

3.6.5 Above ground biomass

At anthesis and maturity, three plants from each subplot were cut at ground level, dried and weighed by an electric balance to determine mean dry matter production as kilogram per hectare.

3.7 Harvest index

3.7.1 Pod harvest index

Pod harvest index (PHI) was calculated according to Assefa *et al.* (2013) as the ratio of grain yield to pod dry weight whereas crop harvest index was calculated as the ratio of seed yield to above ground biomass (Equation 6 and 7).

$$PHI = (GY/PW) * 100 \quad (6)$$

$$CHI = (GY/SBY) *100 \quad (7)$$

3.8 Evapotranspiration and Water use efficiency

Crop water use "evapotranspiration" was determined using the water balance equation by Songsri *et al.* (2009) given as;

$$ET = I + P + (\Theta i - \Theta f) - D - R \quad (8)$$

where ET is evapotranspiration (mm), I is the irrigation applications , P is precipitation, Θi is the initial soil moisture at sowing , Θf is the soil moisture at harvest, D is the soil water drainage and R is the surface runoff. Runoff and drainage were assumed negligible and were not measured. Where irrigation is not applied I = 0.

Water use efficiency based on grain yield (WUE_{GY}) and above ground biomass (WUE_{AGB}) was calculated according to Songsri *et al*. (2009) as;

$$WUE_{AGB} (kg\ ha^{-1}mm^{-1}) = \frac{AGB(kg/ha)}{ET(mm)} \quad (9)$$

$$\text{WUE}_{GY}\ (\text{kg ha}^{-1}\text{mm}^{-1}) = \frac{\text{GY(kg/ha)}}{\text{ET(mm)}} \quad (10)$$

3.9 Rainfall use efficiency

Rainfall use efficiency (RUE) was calculated as the ratio of grain yield (GY) produced per total precipitation (TP) using the accumulated rainfall at the experimental site from emergence to maturity (Chen *et al*., 2003).

$$\text{RUE} = \text{GY (kg ha}^{-1}\text{)/TP (mm)} \quad (11)$$

CHAPTER FOUR

RESULTS

4.1 Climatic conditions of the experimental sites

4.1.1 Soil properties

The physical properties of the soils on the experimental sites showed that Sebele had sandy loam soil whereas Hukuntsi had a sandy soil (Table 4.1). Basically the soils had poor soil fertility. This was supported by the low levels of basic cations (K, Ca, Mg, Na). Sandy soils generally have low cation exchange capacity (CEC), meaning they have less ability to hold and retain and exchange nutrients.

4.1.2 Weather conditions

The 2014/2015 growing season started with showers from mid-October until the end of November in Sebele and Hukuntsi (Figure 4.1). The total rainfall accumulated from sowing to physiological maturity was 145mm in Sebele and 118mm in Hukuntsi. Rainfall was very low compared to the average of 353mm (Sebele) and 383 (Hukuntsi) for the ten year (2004-2014) period recorded at the sites. In Sebele there was a dry spell extending from the second week of January until the fourth week of February. However in Hukuntsi, the distribution was more favourable since the greater proportion of rainfall occurred during flowering of most genotypes.

The air temperature during the growing season in both sites was normal; maximum temperatures were slightly high during vegetative development in Hukuntsi as compared to Sebele (Figure 4. 2). The highest temperatures in February coincided with the reproductive stage of development. From February to May minimum and maximum temperatures were the same in the two sites. Generally temperatures in the experimental sites were high during the vegetative to flowering stages and decreasing with the maturity stage.

4.2 Selection of the six genotypes for study

Figure 4.3 indicates that grain yield decreased with increasing days to flowering and maturity. The final six genotypes had fewer days to flowering as well as maturity as indicated by R^2 values. The relationships between grain yield with flowering and maturity for the eighty five genotypes was weak (Figure 4.3a and b) while these relationships were strong for the six selected genotypes.

Furthermore the six genotypes produced higher grain yield compared to the rest (Figure 4.3a and b).

4.3 Effect of soil water deficit on plant morphology

4.3.1 Days to flowering

Analysis of variance results for days to flowering showed that there was a significant difference ($P<0.0001$) among the water treatments and genotypes (Table 1: Appendix 1). As shown in Figure 4.4a, the irrigated genotypes reached the mean days to flowering by about 1 to 20 days earlier than the rainfed. In this regard, BCA 001 and BCA 019 were significantly earlier than other genotypes under both water regimes, ($P<0.05$). However, BCA 009 flowered late than the rest of the genotypes. A significant interactive effect of treatments and genotypes was also observed at $P<0.0001$ (Table 4.1: Appendix).

4.3.2 Days to maturity

The effect of soil water deficit on the mean number of days to maturity was significant at $P<0.0001$. Irrigated genotypes reached physiological maturity earlier (Figure 4.4b). Analysis revealed that genotypes also had a significant effect ($P<0.0001$) on the days to maturity (Table 1: Appendix). Differences among genotypes were found to be significant ($P<0.05$); genotype BCA 019 reached physiological maturity earlier while BCA 009 was the last to mature. The interaction between the water treatments and genotypes was also significant $P<0.0001$.

4.3.3 Plant height

Treatment variation on plant height is presented in Figure 4.4c. Cowpea genotypes varied significantly at $P<0.05$ in response to growth under water treatments; irrigated plants were taller than those under water deficit. BCA 009 had taller plants while BCA 019 had the shortest under both conditions. An insignificant distinction between BCA 009 and BCA 013 was observed in the control whereas under water deficit experiment, similarities were noted in BCA 002, BCA 016 and BCA 013. The interaction between water and genotypes was significant ($P<0.0001$) (Table 1: Appendix).

4.3.4 Canopy spread

Cowpea response to water regime was significant ($P<0.0001$) on the mean canopy spread with the water deficit plants having a lower canopy spread than the irrigated ones (Table 1:Appendix). Genotypes responded significantly ($P<0.05$) among each other; BCA 016 had more spread under both water levels than BCA 001 which had the shortest spread. Between the irrigated (BCA 002, BCA 016, BCA 013, BCA 009) the difference was insignificant even though the longest spread (293cm) was recorded in BCA 002 which was followed by BCA 016 (Figure 4.4d). The interaction between genotypes and water regimes was significant ($P<0.0001$) as indicated in Table 1: Appendix.

4.3.5 Stem diameter

Water deficit reduced the average stem diameter by 14 to 31% (Table 4.2). The highest reduction was observed in BCA 019 and BCA 002. Variations among genotypes were significant at $P<0.05$; under irrigated plants, BCA 009 had the highest diameter of 21.68mm while the lowest (10.25mm) was recorded in BCA 001. A similar trend was observed in the rainfed experiment in which BCA 009 had the highest diameter of 17.36mm despite it being significantly similar to BCA 013. The interaction among the variables was not significant ($P>0.0001$) (Table 4.2).

4.4 Effect of soil water deficit on plant leaf characteristics

4.4.1 Number of leaves

Genotypic response of cowpea to water regimes on the mean number of leaves is presented in Table 4.3. Water deficit significantly reduced the mean number of leaves, the interaction among the water regimes and genotypes was however insignificant. Non significant differences at $P>0.05$ were observed among genotypes BCA 002, 016, 013 and 009 with respect to the number of leaves on both conditions. Nevertheless, the lowest number of leaves was found in BCA 019 (30) and 001 (26) under rainfed conditions.

4.4.2 Leaf area

As indicated in Table 4.3, the overall mean leaf area was significantly decreased by water deficit at $P<0.0001$. The mean leaf area under irrigated was $1.13m^2$ whereas rainfed had $0.50m^2$. Among the genotypes, significant differences were observed at $P<0.05$. Genotypes BCA 009 and BCA 001 had the highest leaf areas of $2.13m^2$ and $0.81m^2$ under irrigated and rainfed conditions respectively. Under the irrigated experiment, genotypes BCA 002, BCA 013 and BCA 016 were significantly similar, while under rainfed BCA 002 and BCA 009 were statistically similar but significantly different from the rest of the genotypes (Table 4.3).

4.4.3 Leaf area index

Leaf area index showed a significant ($P<0.0001$) variation among water regimes and genotypes. The interaction between water regimes and genotypes was nonetheless insignificant (Table 4.3). The results indicated a decreasing leaf area index (LAI) with soil water deficit. A significant distinction among the genotypes was observed at $P<0.05$. No significant variation was observed amongst BCA 009 and 013 in spite of the latter having a higher value under both conditions. As in leaf area, a similar observation was made in BCA 009 and 001 where the highest and lowest values were recorded under irrigated and rainfed conditions respectively.

4.4.4 Specific leaf area

Highly significant differences ($P<0.0001$) were observed for mean specific leaf area (SLA) subjected to water deficit; the mean ranged from 30.49 to 53.44 cm^2/g for the control and 12.67 to 39.58 cm^2/g for the water stressed plants. The interaction among the factors was also significant at $P<0.0001$ (Table 4.3). Genotypes were significantly different from each other ($P<0.05$), hence in the control, BCA 002 had the highest SLA followed by BCA 016 while BCA 001 and 019 were the lowest. For the water deficit trial, BCA 019 maintained the lowest value and the highest was noted in BCA 013 (Table 4.3).

Table 4.1: Soil physico-chemical properties at the experimental sites

Soil properties	**Location**	
	Sebele	**Hukuntsi**
Soil type	Sandy loam	Sandy
pH ($CaCl_2$)	5.6	5.2
Organic Carbon (%)	1.8	0.7
P (ppm)	5.2	0.02
Ca (cmol/kg)	1.3	1.76
Mg (cmol/kg)	0.7	0.35
K (cmol/kg)	0.76	0.10
Na (cmol/kg)	0.17	0.09
CEC (cmol/kg)	4.60	3.06
EC (mS/m)	1.97	1.84

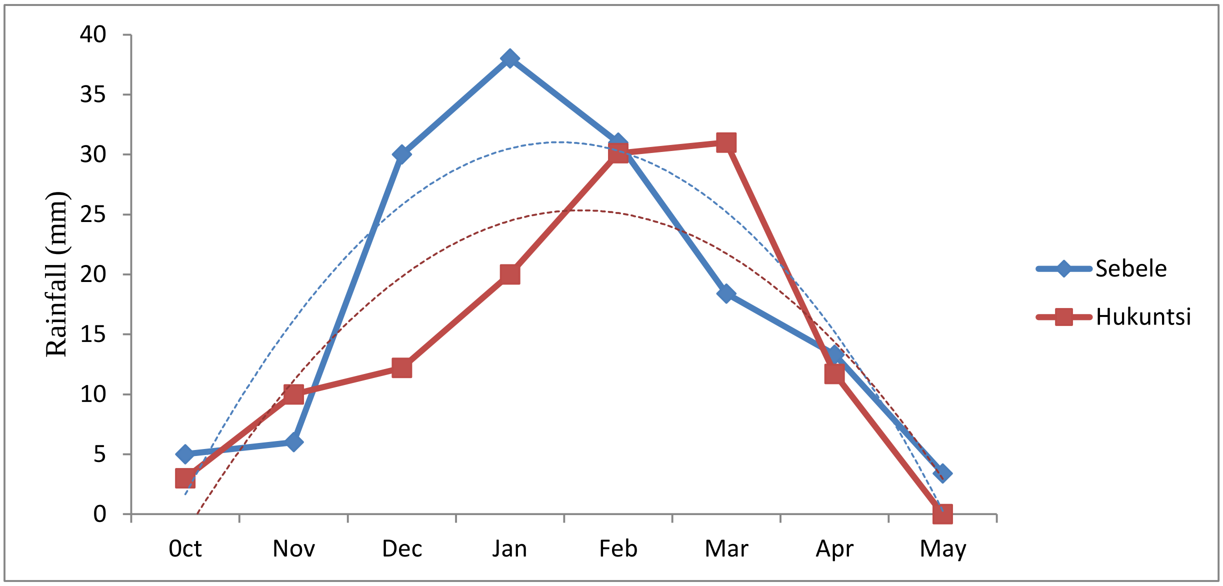


Figure 4.1:Rainfall distribution during cowpea development at Sebele and Hukuntsi (2014/15)

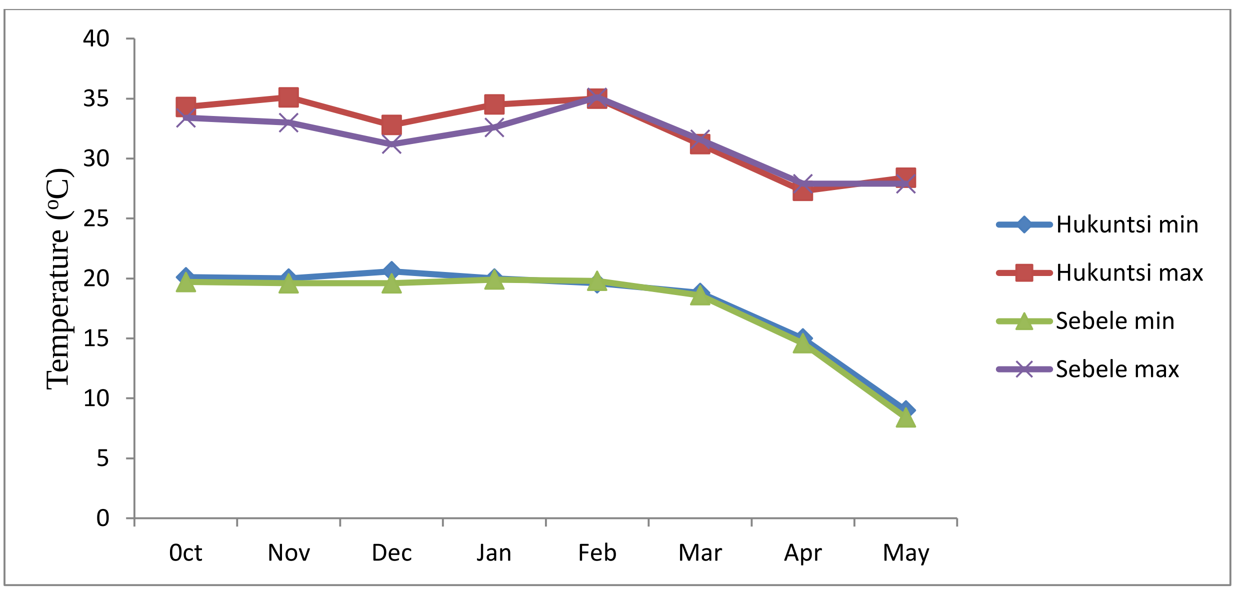


Figure 4.2: Monthly minimum and maximum temperatures for Sebele and Hukuntsi during cowpea development in 2014/15.

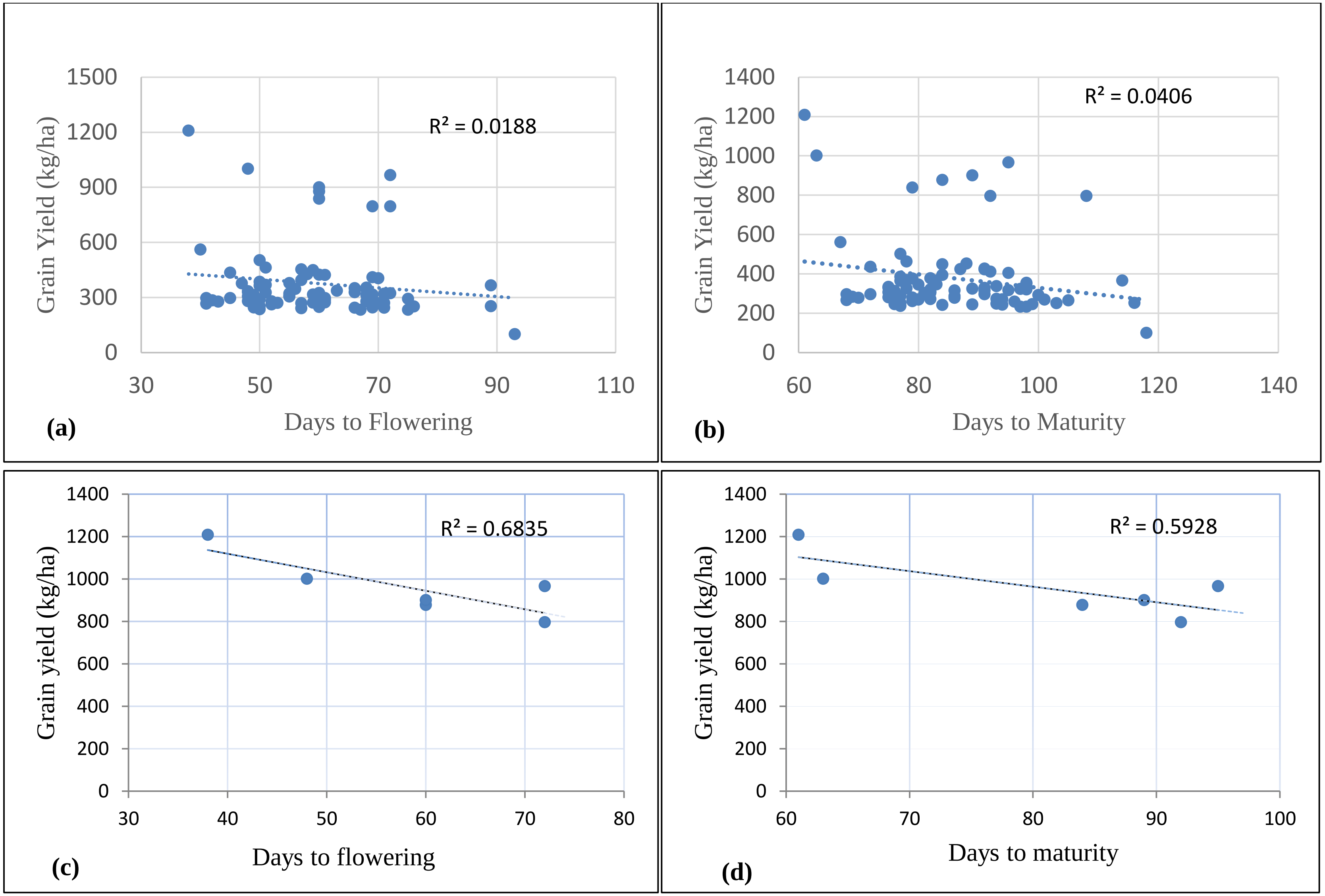


Figure 4.3: Relationship of grain yield with days to flowering and maturity for the eighty five genotypes (a and b) and for the final six genotypes (c and d).

Table 4.2: Effect of soil water deficit on stem diameter of cowpea grown at Sebele

Genotype	Irrigated (mm)	Rainfed (mm)
BCA 001	10.25^{e}	7.10 (31) ^{d}
BCA 019	14.15^{cd}	9.75 (31) ^{c}
BCA 002	11.80^{ed}	9.50 (19) ^{c}
BCA 016	16.48^{cb}	12.40 (24.7) ^{b}
BCA 013	18.52^{ba}	15.93 (13.9) ^{a}
BCA 009	21.68^{a}	17.36 (19.9) ^{a}
Mean	15.48	12.0 (22.5)
Genotype (G)	***	
Water (W)	***	
G*W	ns	

Means followed by the same letter within a column are not significantly different at 5% probability level using the Least Significant Difference (LSD) test while *** , ns and G*W indicates significance at 0.0001 , non-significance and interactions respectively. Values in parenthesis indicate reductions (%) due to water deficit.

Table 4.3: Effect of soil water deficit on leaf characteristics of cowpea genotypes in Sebele

Genotype	Number of leaves/plant		Leaf area (m^2)		Leaf Area Index		Specific Leaf Area (cm^2/g)	
	I	R	I	R	I	R	I	R
BCA 001	50^{b}	26^{b}	0.48^{c}	0.24^{c}	0.86^{d}	0.42^{c}	30.49^{c}	17.52^{de}
BCA 019	42^{b}	30^{b}	0.57^{c}	0.20^{c}	1.01^{d}	0.36^{c}	31.42^{c}	12.67^{e}
BCA 002	92^{a}	66^{a}	1.27^{b}	0.71^{a}	2.26^{bc}	1.26^{b}	53.44^{a}	32.61^{bc}
BCA 016	95^{a}	59^{a}	1.20^{b}	0.51^{b}	2.13^{dc}	0.90^{b}	51.78^{ba}	25.22^{dc}
BCA 013	105^{a}	71^{a}	1.10^{b}	0.51^{b}	2.95^{a}	2.33^{a}	44.26^{c}	41.58^{a}
BCA 009	110^{a}	66^{a}	2.13^{a}	0.81^{a}	4.15^{a}	2.05^{a}	40.78^{bc}	37.66^{ba}
Mean	83	53	1.13	0.50	2.07	1.22	41.25	28.33
Genotype (G)	***		***		***		***	
Water (W)	***		***		***		***	
G*W	ns		***		ns		***	

Means followed by the same letter within a column are not significantly different at P≤0.05
*** and ns indicate significant difference at P<0.0001 and non- significant while I = irrigated, R = rainfed.

4.5 The effects of soil water deficit Plant water relations

4.5.1 Relative water content (RWC%)

There was a significant treatment effect as well as a significant treatment by genotype interaction effect on relative water content (RWC) at $P<0.0001$. Relative water content was higher in the control than the water deficit treatment and this accounted to 21% of the total variation (Table 2: Appendix). At $P<0.05$, significant variations among genotypes were observed. BCA 019, BCA 002 and BCA 016 were similar but significantly different from other genotypes. For rainfed treatment, the above mentioned genotypes were not significantly ($P>0.05$) different except for BCA 016 which was replaced by BCA 009 (Figure 4.5a).

4.5.2 Plant survival (%)

Significant variations among genotypes with regard to survival under a water deficit condition were observed at $P<0.05$. Figure 4.5b indicates that BCA 001, BCA 009 and BCA 016 were similar and had more plant survivors than BCA 013, BCA 002 and BCA 019. For the latter less than 50% of the plants survived drought.

4.6 The effect of soil water deficit on grain yield and its components

4.6.1 Number of pods per plant

The number of pods per plant was significantly affected by water regimes as summarized in Figure 4.6a. Table 3 (Appendix) also indicates a significant ($P<0.0001$) genotype by water interaction effect. Differences between genotypes under each water condition were also highly significant ($P<0.0001$). The highest number of pods recorded was 108 and 92 for BCA 016 under rainfed and irrigated conditions. Twenty eight pods was the lowest number recorded for BCA 019 under rainfed whereas in the control BCA 001 had the lowest number of 44. No statistical differences were observed in genotypes BCA 001, BCA 019, BCA 002 and BCA 016 under both conditions excluding BCA 016 under rainfed.

4.6.2 Pod length

Results in Figure 4.6b indicated that pod length was significantly reduced by water deficit. In response to water regimes, genotypic differences were significant in pod length ($P<0.05$). BCA 013 had the longest pods while BCA 009 had the shortest. Comparatively under rainfed, BCA 009 maintained the shortest and the longest pods were recorded in BCA 016. A significant treatment by genotype interaction was also noted at $P<0.0001$ (Table 3: Appendix).

4.6.3 Number of seeds per pod

Water deficit significantly reduced the mean number of seeds per pod ($P<0.0001$). However there was no significant interaction among water treatments and cowpea genotypes (Table 3: Appendix). Genotypic differences among treatment means were observed at $P<0.0001$. As indicated in Figure 4.7, BCA 019 had more seeds followed by BCA 016 and BCA 013. No significant differences were observed among the rest of the genotypes under the control. In comparison to the irrigated trials, BCA 019 still maintained the highest number of seeds but was significantly not different from BCA 013 and BCA 016. BCA 009 had the lowest number (11 and 9) under well watered and rainfed conditions respectively.

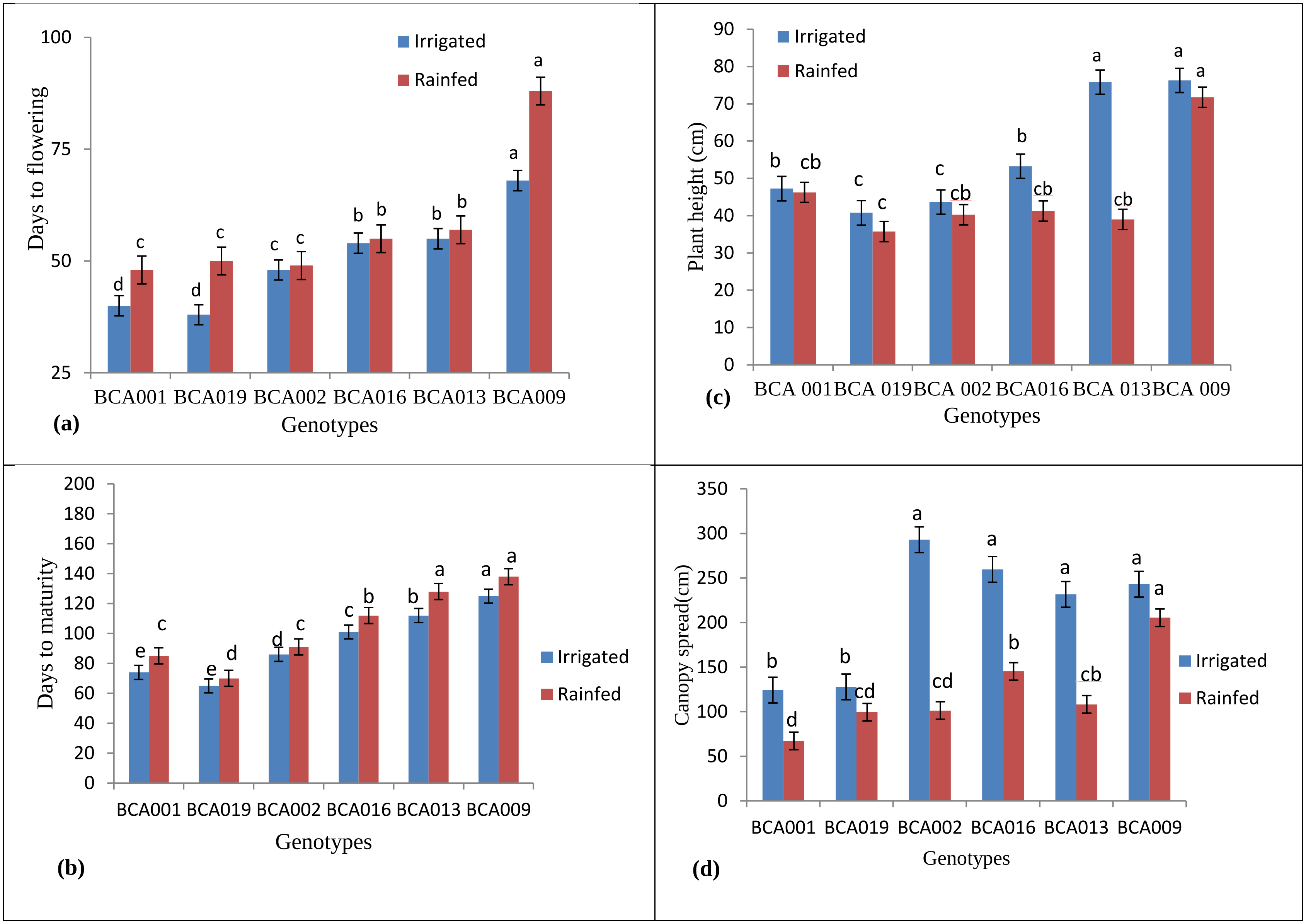
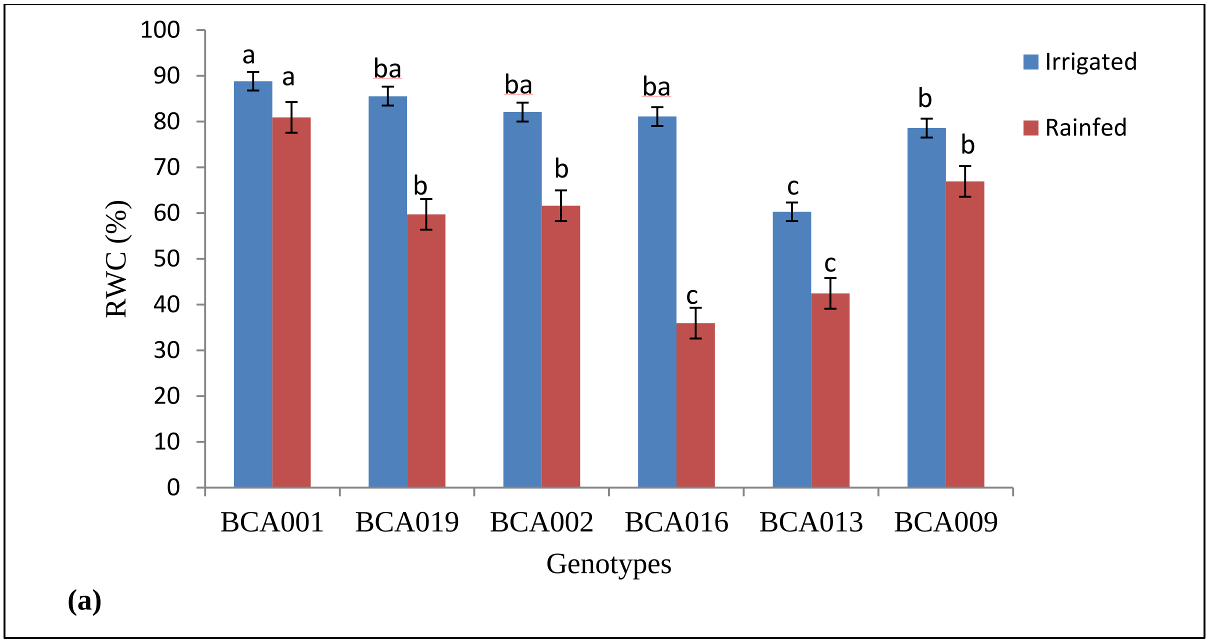


Figure 4.4: Effect of soil water deficit on plant morphology under irrigated and rainfed conditions at Sebele. Error bars indicate standard error of the means. Different letters on the bars of each genotype indicate significant differences at P<0.05.



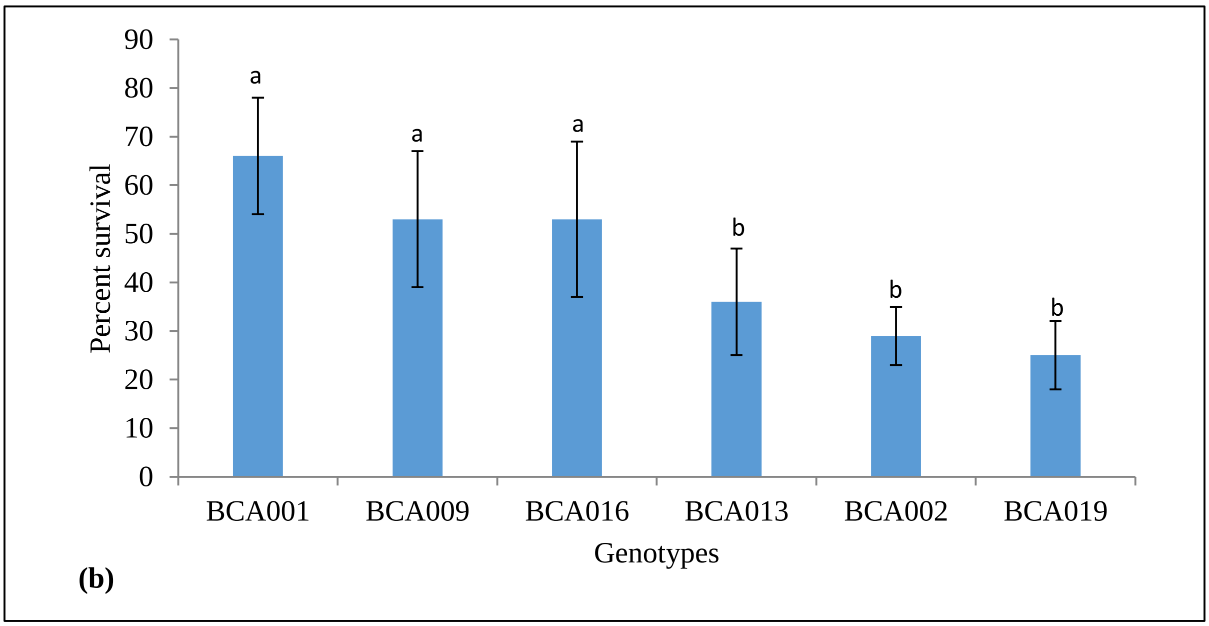


Figure 4.5:Effect of water deficit on relative water content (RWC%) and percent plant survival of cowpea genotypes as influenced by water deficit at Sebele. Error bars indicate standard error of the means.

In Figure 4.5a, same letters on the bars of each genotype indicate non-significant differences (P>0.05) between irrigated and rainfed conditions. In Figure 4.5b, same letters between bars indicate non-significant differences between genotypes.

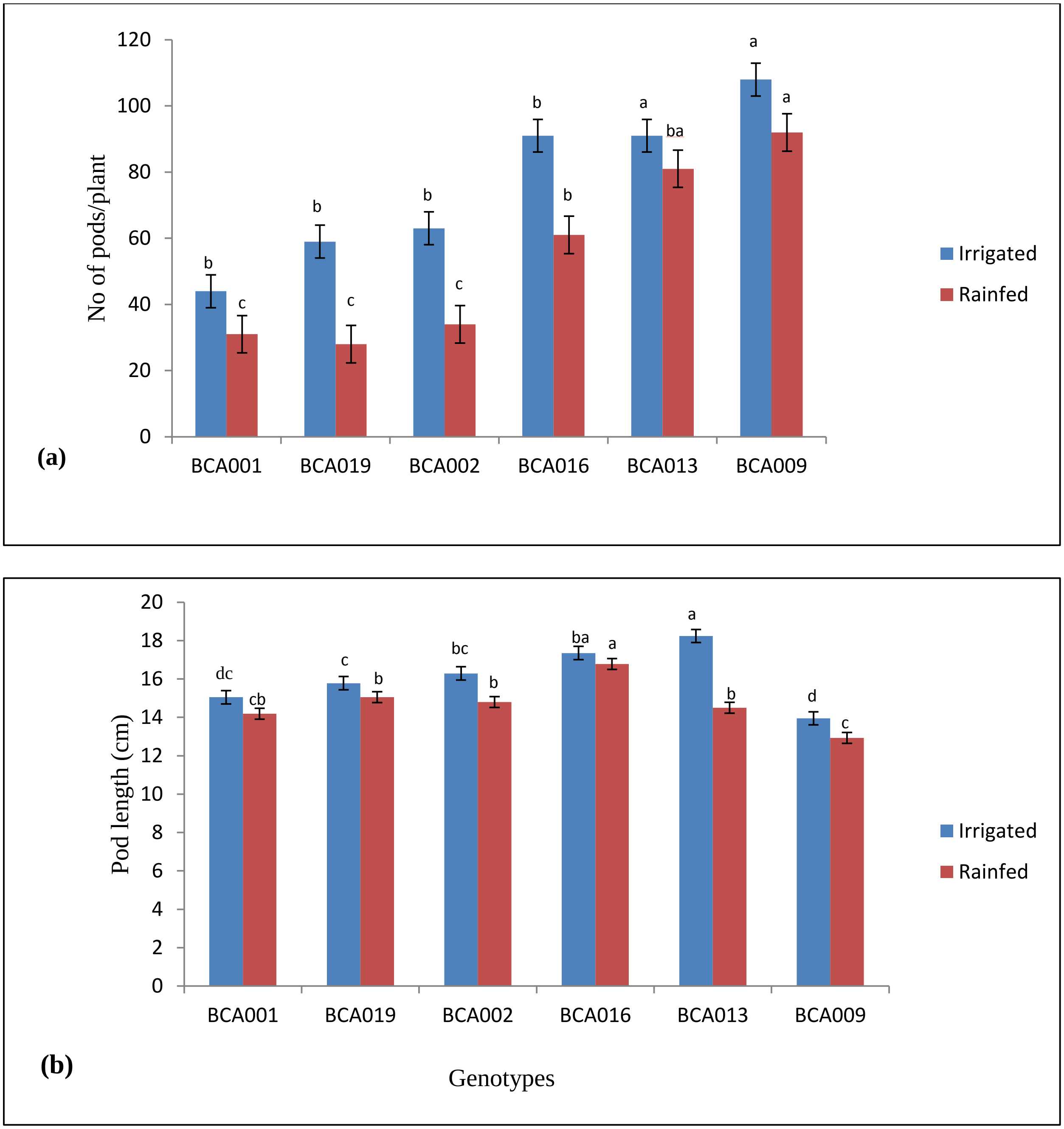


Figure 4.6: Effect of soil water deficit on the number of pods per plant (a) and pod length (b) at Sebele.

Error bars indicate standard error of the means. Same letters on the bars of each genotype indicate non-significant differences (P>0.05) between irrigated and rainfed conditions.

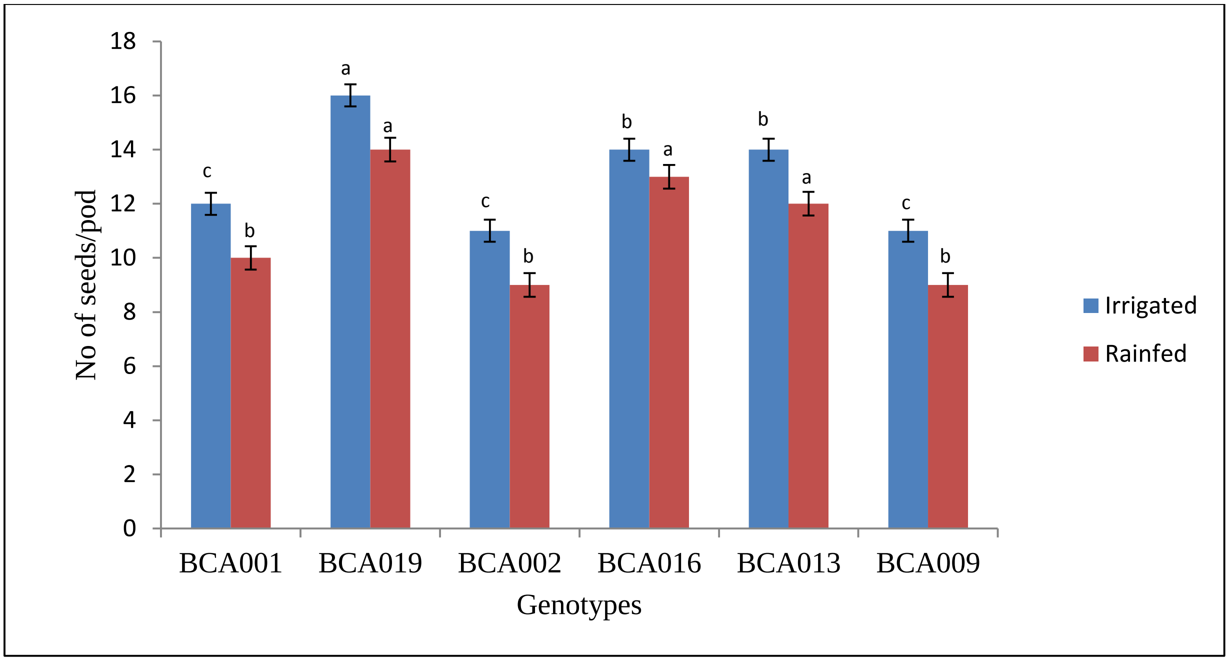


Figure 4.7: Effect of soil water deficit on the number of seeds per pod at Sebele.

Error bars indicate standard error of the means. Same letters on the bars of each genotype indicate non-significant differences (P>0.05) between irrigated and rainfed conditions.

4.6.4 100 Seed weight

On average, the weight of 100 seeds was significantly (P<0.05) affected by water treatment; water deficit reduced the overall seed weight. The interaction between water and genotypes was also significant at P<0.0001 as indicated in Table 4.4. Genotypic variations in response to the treatment means were observed at P<0.05; BCA 009 produced heavier seeds (41.5 and 30.5g) under irrigated and rainfed trials respectively. BCA 019 had the lowest weight of 19.4g under the control whereas in rainfed condition the lowest of 130g from BCA 001 was recorded.

4.6.5 Pod harvest Index

Results in Table 4.4 illustrated that pod harvest index (PHI) increased significantly with irrigation despite having no significant interaction effect among water and the cowpea genotypes used ($P<0.0001$). Pod harvest index ranged from 78.60 to 87.32 and 58.63 to 78.79 in the control and rainfed experiments respectively. Significant genotypic differences at $P<0.05$ were observed; under the irrigated plants, BCA 001 had the highest PHI and the rest of the genotypes were statistically similar in exclusion of BCA 019. For the rainfed demonstration, the highest PHI was noted in BCA 013 whilst BCA 002 had the lowest.

4.6.6 Crop harvest index

Analysis of variance in Table 4.4 showed that watering regimes had a significant ($P<0.0001$) effect on the overall mean performance of cowpea genotypes with respect to crop harvest index (CHI). A significant interaction between water and genotypes was also significant at $P<0.0001$. The water deficit treatment significantly reduced CHI by almost 50%. Significant distinctions were also present between genotypes in the water treatments ($P<0.05$). In this regard, BCA 001 had the highest CHI of 53.50 compared to BCA 009 which had the lowest of 14.34 although it was not statistically different from BCA 016. Comparatively, on the water deficit trial, BCA 013 had the highest CHI followed by BCA 001, BCA 002 and BCA 009 which were statistically the same while BCA 016 still had the lowest value.

Table 4.4 Yield components of cowpea genotypes at different water treatments at Sebele.

Genotype	100 SW (g)		PHI		CHI	
	I	R	I	R	I	R
BCA 001	19.9^{d}	13.0^{e}	87.32^{a}	64.7^{bc}	53.50^{a}	17.99^{ba}
BCA 019	19.4^{d}	17.0^{e}	78.60^{b}	67.14^{bac}	28.24^{b}	15.16^{b}
BCA 002	31.8^{b}	24.8^{c}	79.55^{ba}	58.63^{c}	39.89^{b}	22.57^{ba}
BCA 016	25.5^{c}	21.6^{d}	79.93^{ba}	74.14^{ba}	23.13^{c}	13.65^{b}
BCA 013	31.1^{b}	28.5^{b}	85.72^{ba}	78.79^{a}	38.82^{b}	24.81^{a}
BCA 009	41.5^{a}	30.5^{a}	78.76^{ba}	72.84^{ba}	14.34^{c}	18.87^{ba}
Mean	27.8	27.0	81.65	69.37	34.65	18.84
Genotype (G)	***		****		***	
Water (W)	***		***		***	
G*W	***		ns		***	

Means followed by the same letter within a column are not significantly at P>0.05. I and R indicate irrigated and rainfed conditions. G*W = interaction while *** and ns represent significance at P<0.0001 and non-significance respectively.

4.6.7 Above ground biomass

As summarized in Figure 4.8a significant differences were observed for mean above ground biomass subjected to water deficit in which the mean ranged from 1326 to 2459 kg/ha and 606 to 1832 kg/ha for the irrigated and rainfed treatments respectively. Genotypic variations in response to water treatments were significant ($P<0.05$); the highest above ground biomass under the control was produced by BCA 009 although it was insignificantly different from BCA 016. A similar trend was observed under water deficit in which BCA 009 had the highest biomass; nevertheless it was significantly different from BCA 016. A significant interaction between water treatments and genotypes was also observed at $P<0.0001$ (Table 4: Appendix).

4.6.8 Grain yield

As indicated in Figure 4.8b, water deficit reduced the grain yield by more than half in most genotypes. The differences between genotypes was also significant at $P<0.05$; in the irrigated trial BCA 019 yielded more (636kg/ha) but was not significantly different from other genotypes except BCA 009. Comparatively there was no variation among rainfed BCA 001 and BCA 013 although the latter yielded more. The analysis of variance also showed that the interaction between watering treatments and genotypes was significant at $P<0.001$ (Table 4: Appendix).

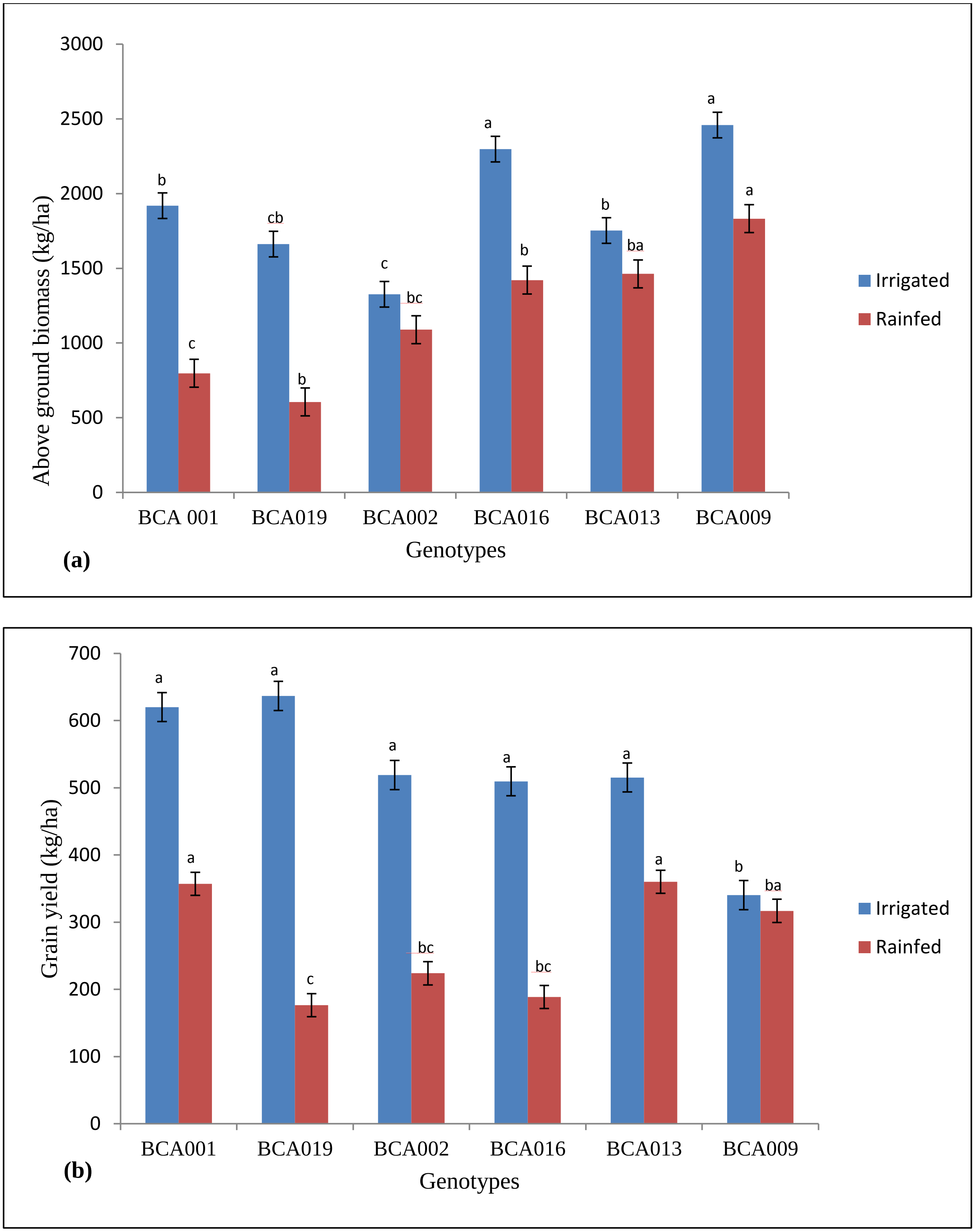


Figure 4.8: Above ground biomass and grain yield of cowpea genotypes under irrigated and rainfed treatments at Sebele.

Error bars indicate standard error of the means. Same letters on the bars of each genotype indicate non-significant differences (P>0.05) between irrigated and rainfed conditions.

4.7 Evapotranspiration (Water Use)

The effect of soil water deficit on crop water use of cowpea genotypes is presented in Table 4.5. Water use depended largely on water regimes in which the highest usage was observed in the irrigated than the rainfed plants. The reduction in WU due to deficit was significant at P<0.0001; genotypes BCA 019 had a high decline of 91.6% with the lowest decline of 44.5% visible in BCA 009. In overall, a mean decline of 83% in all the six genotypes was recorded. Genotypes also reacted significantly (P<0.05) in water use under all water regimes (Table 4.5). BCA 009 had the lowest water use while the highest consumer was BCA 002; this was recorded in the control experiment. Comparatively, the lowest consumer was BCA 019 in the rainfed treatment. The interactive effect of water regimes and cowpea genotypes on water use was however not significant (P>0.05).

Table 4.5: Mean water use of cowpea genotypes in response to water regimes at Sebele.

Genotype	Water Use (mm)		
	Irrigated	Rainfed	% Reductions
BCA 001	657.85[c]	120.80[a]	81.6
BCA 019	678.43[bc]	56.51 (91.6)[b]	91.6
BCA 002	880.83[a]	168.4 (80.9)[a]	80.9
BCA 016	877.65[ba]	133.74 (84.8)[a]	84.8
BCA 013	748.24[bac]	148.15 (48.8)[ba]	48.8
BCA 009	814.8[bac]	150.97 (44.5)[a]	44.5
Mean	776.30	129.76	
Genotypes	***		
Water	***		
G*W	ns		

Means followed by the same letter within a column are not significantly at P>0.05. G*W indicates interaction while *** and ns represent significance at P<0.0001 and non-significance respectively.

4.8 Effect of soil water deficit on water use efficiency at anthesis and maturity stages

4.8.1 Anthesis water use efficiency for above ground biomass

The effect of soil water deficit on above ground biomass water use efficiency at the anthesis stage was significant ($P<0.0001$) (Figure 4.9). Genotypes under rainfed conditions were significantly water use efficient than the irrigated ones and the interaction between the water treatments and genotypes was also significant ($P<0.0001$) (Table 5: Appendix). The difference among genotypes were significant ($P<0.05$); BCA 019 had the highest WUE (7.91 and17.32 kg/ha.mm^{-1}) followed by BCA 001 (7.52 and 14.44 kg/ha.mm^{-1}) under irrigated and rainfed conditions respectively. The lowest WUE under irrigation was recorded in BCA 009 although it was not significantly different from the rest of the genotypes. However under rainfed condition BCA 002 had the lowest value.

4.8.2 Maturity water use efficiency for grain yield

Cowpea under water deficit condition recorded significantly ($P<0.0001$) higher WUE compared to their corresponding irrigated genotypes (Figure 4.10a). The average WUE ranged from 0.43 to 0.95 kg/ha.mm^{-1} in the control and 1.33 to 3.15 kg/ha.mm^{-1} under rainfed trial. The interactive effect of watering treatments and genotypes was also significant at $P<0.0001$ (Table 5: Appendix). Among the genotypes, significant differences between treatment means were observed at $P<0.05$; BCA 001 was not significantly different from BCA 019 but significantly different from other genotypes on both conditions. A similar behavior was observed in BCA 002 and BCA 016. Generally, BCA 001 was the most water use efficient with 0.95 and 3.15 kg/ha.mm^{-1} followed by BCA 019 with 0.96 and 3.13 kg/ha.mm^{-1} under irrigated and water deficit conditions respectively.

4.8.3 Maturity water use efficiency for above ground biomass

Statistical analysis revealed a significant effect of watering treatments and genotypes on mean biomass WUE. Cowpea genotypes under water deficit recorded higher values of WUE compared to their corresponding irrigated genotypes (Figure 4.10b). BCA 009 which recorded the highest value of 12.28kg/ha.mm^{-1} under water deficit was the most water use efficient although it was not significantly different from BCA 002, BCA 016 and BCA 013 at P>0.05. Under the control, a reversal trend was observed; genotypes which were less efficient under water deficit (BCA 001 and BCA 019) were among the most efficient despite them being not significantly different from BCA 009 and BCA 016. The highest WUE recorded was 3.10 kg ha^{-1}mm^{-1} in BCA 009 while BCA 002 had the lowest of 1.65 kg ha^{-1}mm^{-1}. A significant interaction between water and genotypes was noted at P<0.01 (Table 5: Appendix).

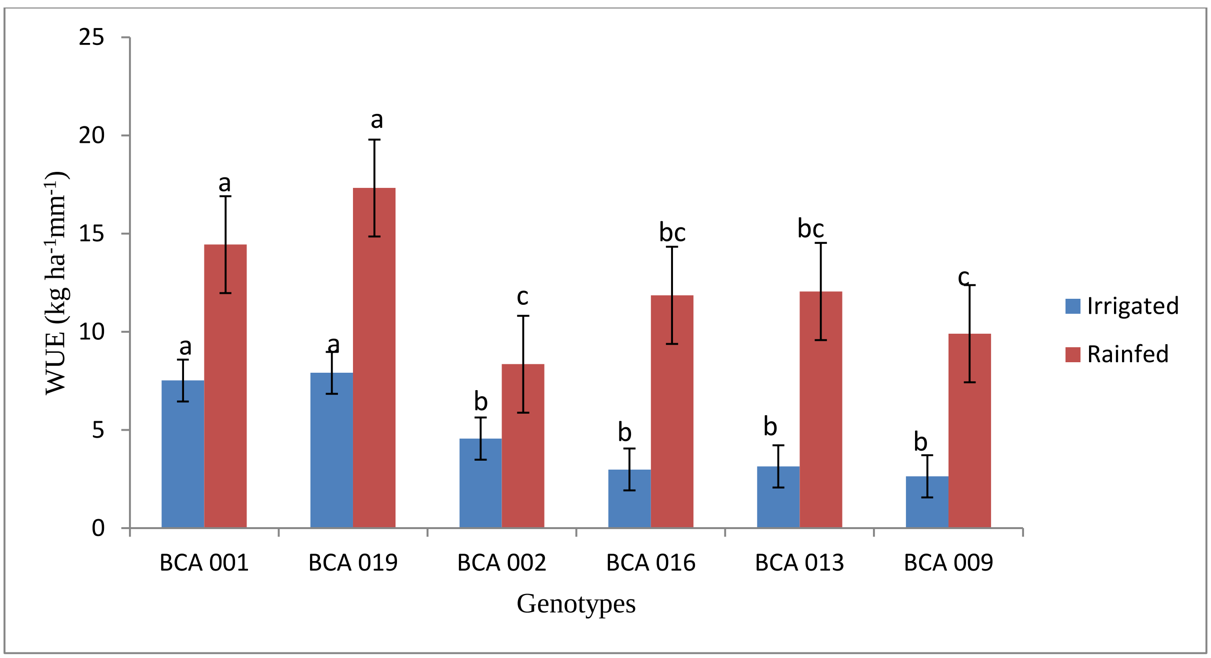


Figure 4.9: Effect of soil water deficit on biomass Water use efficiency (WUE) at the anthesis stage of cowpea genotypes at Sebele.

Error bars indicate standard error of the means. Same letters on the bars of each genotype indicate non-significant differences (P>0.05) between irrigated and rainfed conditions.

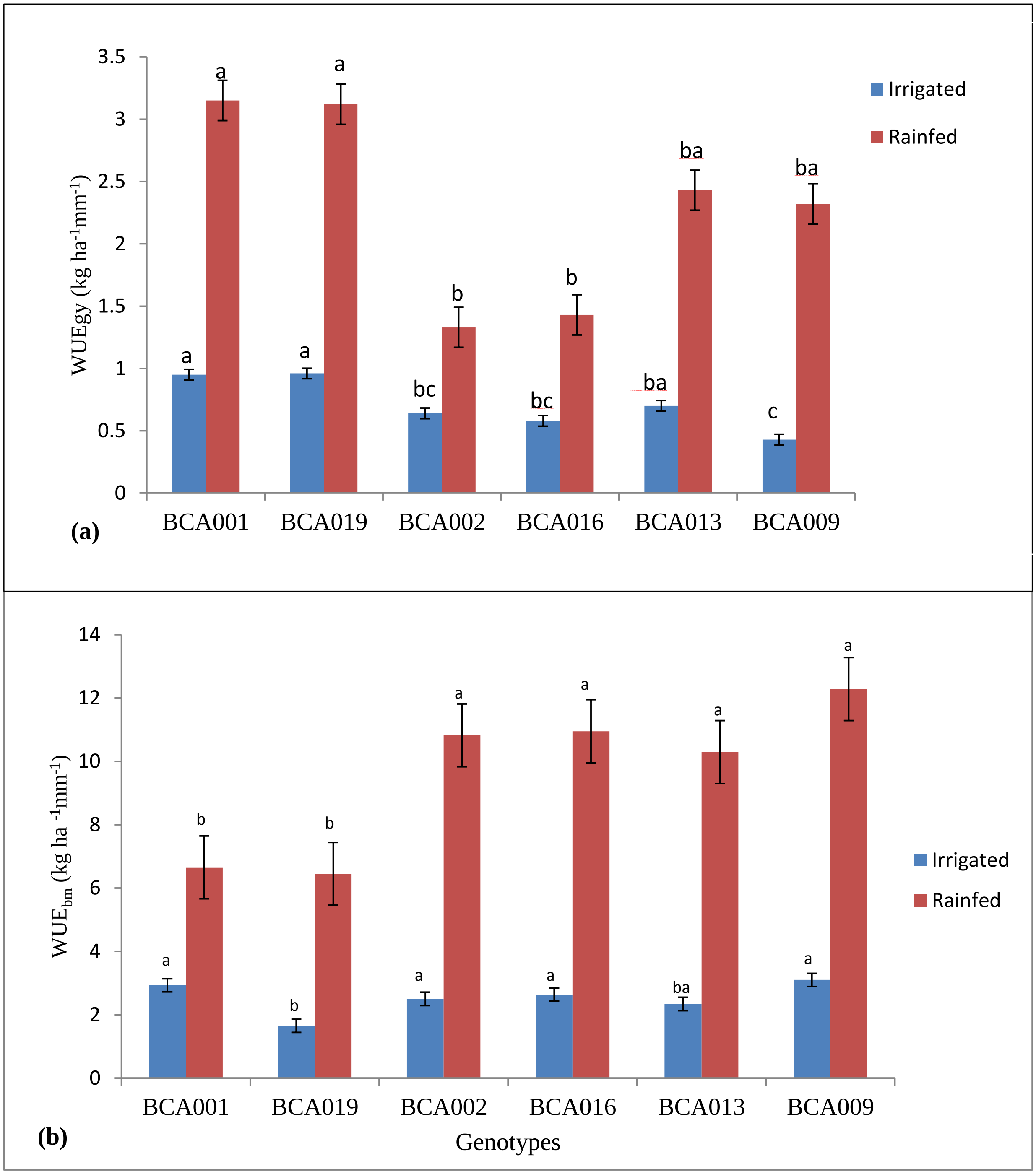


Figure 4.10: Effect of soil water deficit on grain yield (a) and above ground biomass (b) WUE of cowpea genotypes at Sebele. Error bars indicate standard error of the means.

Same letters on the bars of each genotype indicate non-significant differences ($P>0.05$) between irrigated and rainfed conditions.

Hukuntsi differed significantly $P<0.05$. It varied from 2.45 to 3.88 kg ha^{-1}mm^{-1}. The highest RUE was recorded in BCA 001 followed by BCA 019 and BCA 013 which were however not statistically different. BCA 016 and BCA 009 were the least rainfall use efficient genotypes.

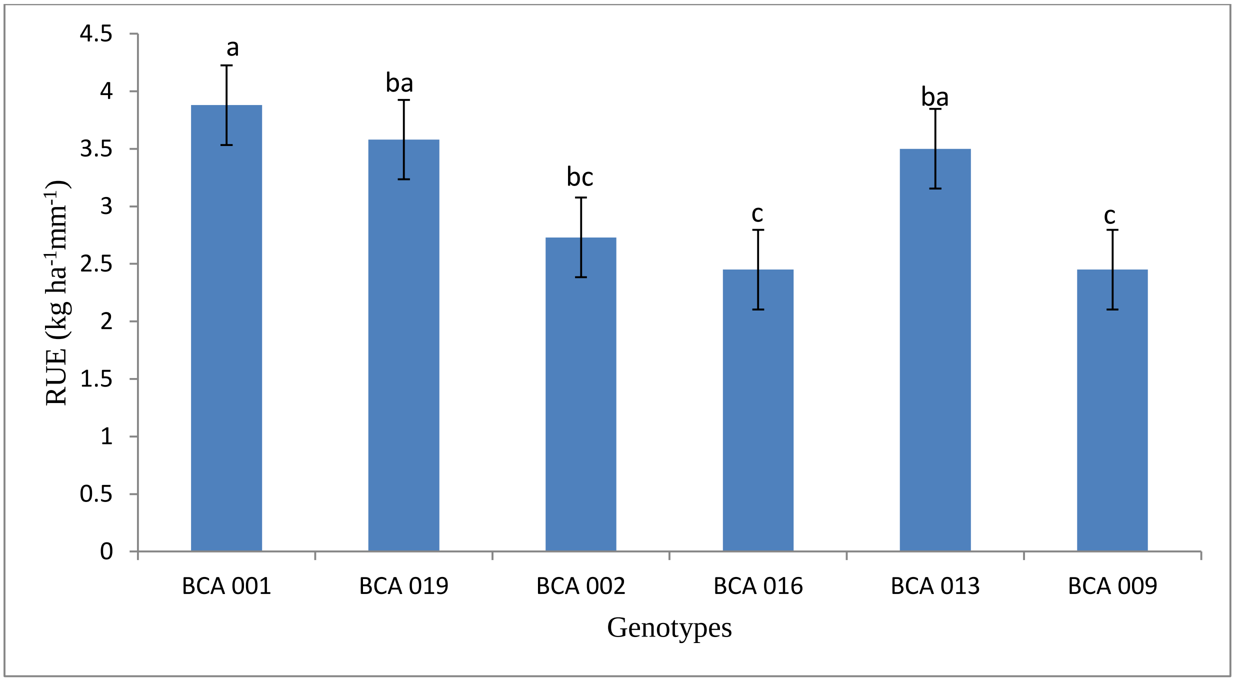


Figure 4.11: Rainfall use efficiency (RUE) of cowpea genotypes at Hukuntsi

Same letters on the bars of each genotype indicate non-significant differences

4.10 Correlation and regression analysis

Figure 4.12 indicates the relationship between grain yield, above ground biomass and water use efficiency (WUE). The relationship between grain yield and evapotranspiration (ET) was a quadratic function and significantly positive under a rainfed condition. Grain yield therefore did not increase when ET exceeded a critical value; in this case about 137mm which is approximately 64% of the measured maximum ET. However, biomass increased linearly with ET. As for the control, the opposite was observed; yield had a negative linear relationship while biomass had a non-linear one. The corresponding correlation coefficients were 0.12, 0.23 and 0.40, 0.05 for yield and biomass under rainfed and irrigated conditions respectively.

Evapotranspiration also had a linear relationship with SLA (R^2 = 0.27, 0.10) (Figure 4.13) and CHI (R^2 = 0.15, 0.11) (Figure 4.14) under rainfed and irrigated conditions respectively. These relationships were non significant for SLA and only negative for CHI under irrigation. With respect to WUE, evapotranspiration was negatively and significantly correlated with WUE (R^2 = 0.41) under rainfed and (R^2 = 0.48) irrigated conditions (Figure 4.15). A significant curvilinear relationship between RWC and WUE was observed under both water regimes; R^2 = 0.49 under rainfed and 0.35 in an irrigated trial (Figure 4.16). As for percent survival versus WUE, the relationship was strongly positive with a coefficient of 0.69 (Figure 4.17). On the other hand, WUE had significantly positive and linear association with yield under rainfed (R^2 = 0.26) while for the irrigated experiment a non-linear positive relationship (R^2 = 0.70) was obtained (Figure 18a and b). With biomass, the correlation was significantly negative (R^2 = 0.14 and 0.12) under rainfed and irrigated conditions (Figure 18c and d) while a positive and weak linear relationship between anthesis WUE and biomass WUE was observed. The corresponding coefficients for the latter were 0.06 and 0.16 in rainfed and irrigated conditions respectively (Figure 4.19).

Furthermore, WUE had a non-linear negative correlation with SLA and CHI as presented in Figures 4.20 and 4.21. Nonetheless under the control there was a negative correlation between CHI and WUE. All these correlations were significant except for CHI under irrigation. Their corresponding coefficients were 0.24, 0.14 and 0.04, 0.45 for SLA and CHI under rainfed and irrigated trials respectively. In summary, WUE had a weak correlation (R^2=0.31) with plant traits under rainfed conditions as indicated in Table 6. In general, WUE had a weak relationship with plant traits under water deficit conditions as indicated in Table 4.6

Regression analysis revealed that WU contributed 12%, 40%, 27%, 15% and 41% to variability in biomass, yield, SLA, CHI and WUE under rainfed conditions. The corresponding contribution of WU for these characters under irrigated conditions was 23%, 5.4%, 10.1%, 11% and 48% respectively. On the other hand the contributions towards WUE by other variables was 49%, 35% (RWC), 26.4%, 70% (yield) and 14%, 12% (biomass) under rainfed and irrigated conditions respectively. In addition, the contribution of percent survival to WUE was 69% whereas anthesis WUE contributed 6 % and 16% towards final biomass WUE in irrigated and rainfed conditions. Meanwhile SLA and CHI contribution to WUE was 24%, 14% and 4%, 45% under rainfed and irrigated conditions respectively.

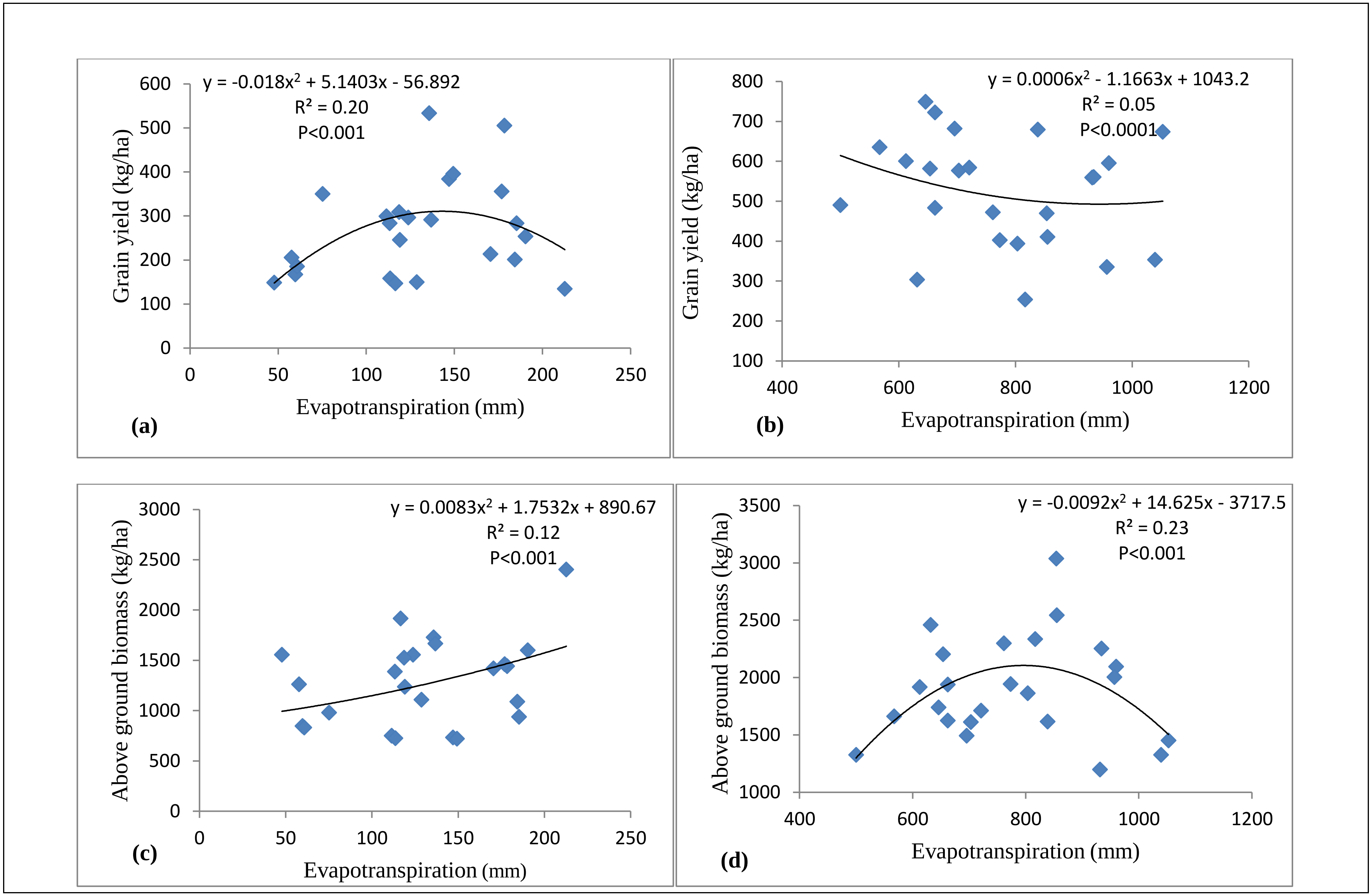


Figure 4.12:Relationship between Evapotranspiration and yield at Sebele.

Grain yield: rainfed (a), irrigated (b)

Above ground biomass yield rainfed (c), irrigated (d)

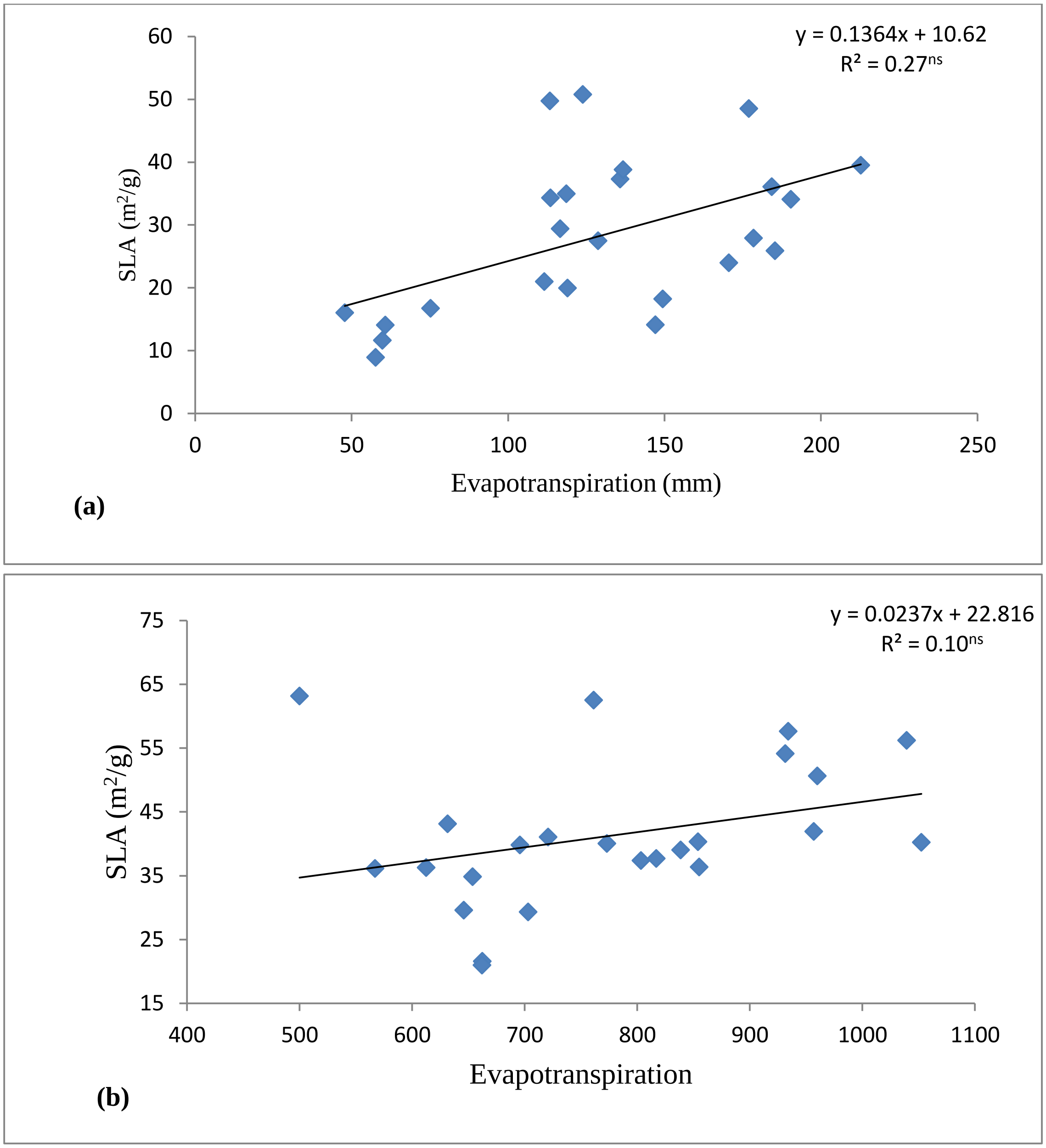


Figure 4.13: Relationship between Specific leaf area (SLA) and Evapotranspiration under rainfed (a) and irrigated conditions (b) at Sebele.

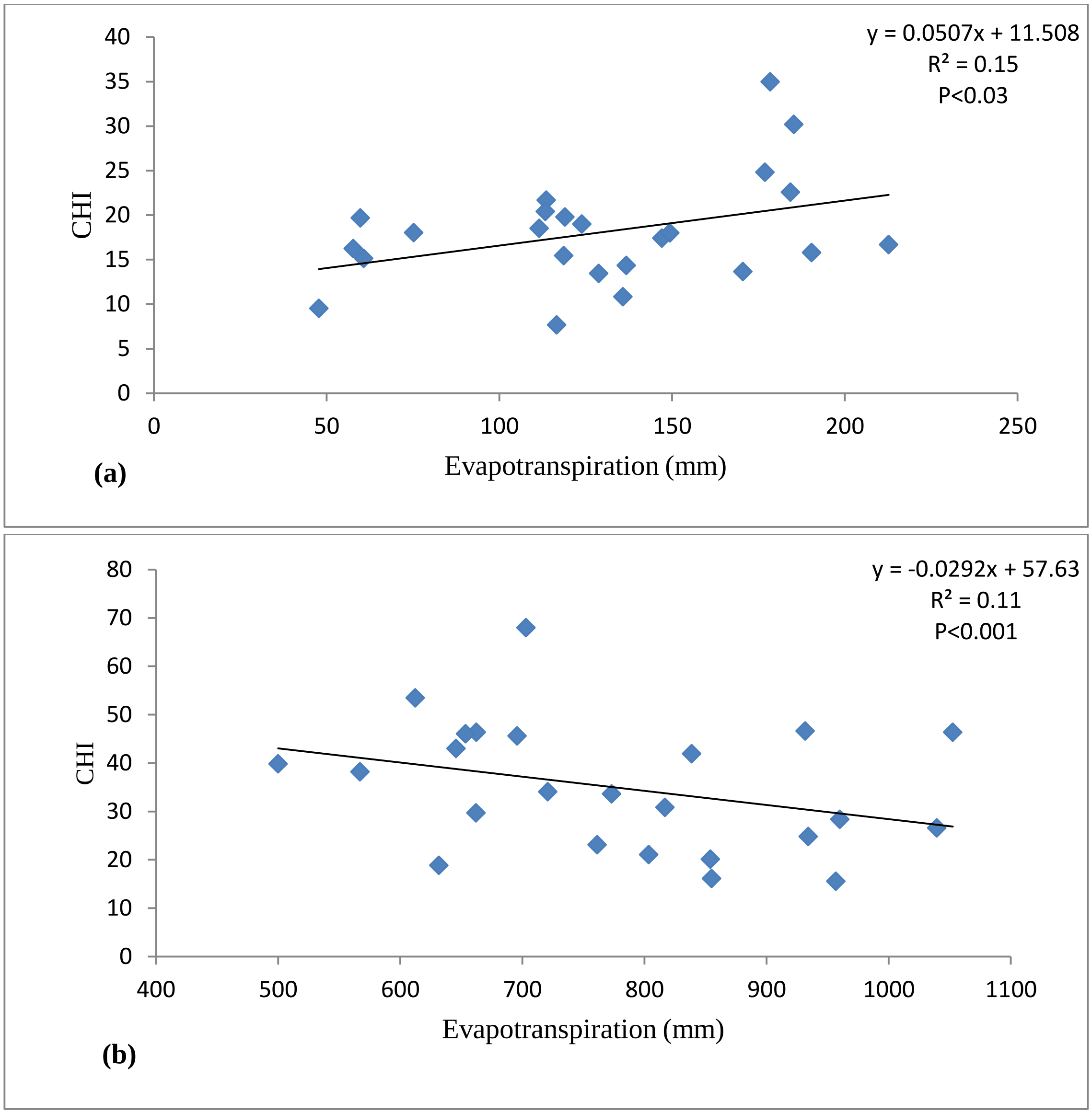


Figure 4.14: Relationship between crop harvest index (CHI) and Evapotranspiration under rainfed (a) and irrigated conditions (b) at Sebele.

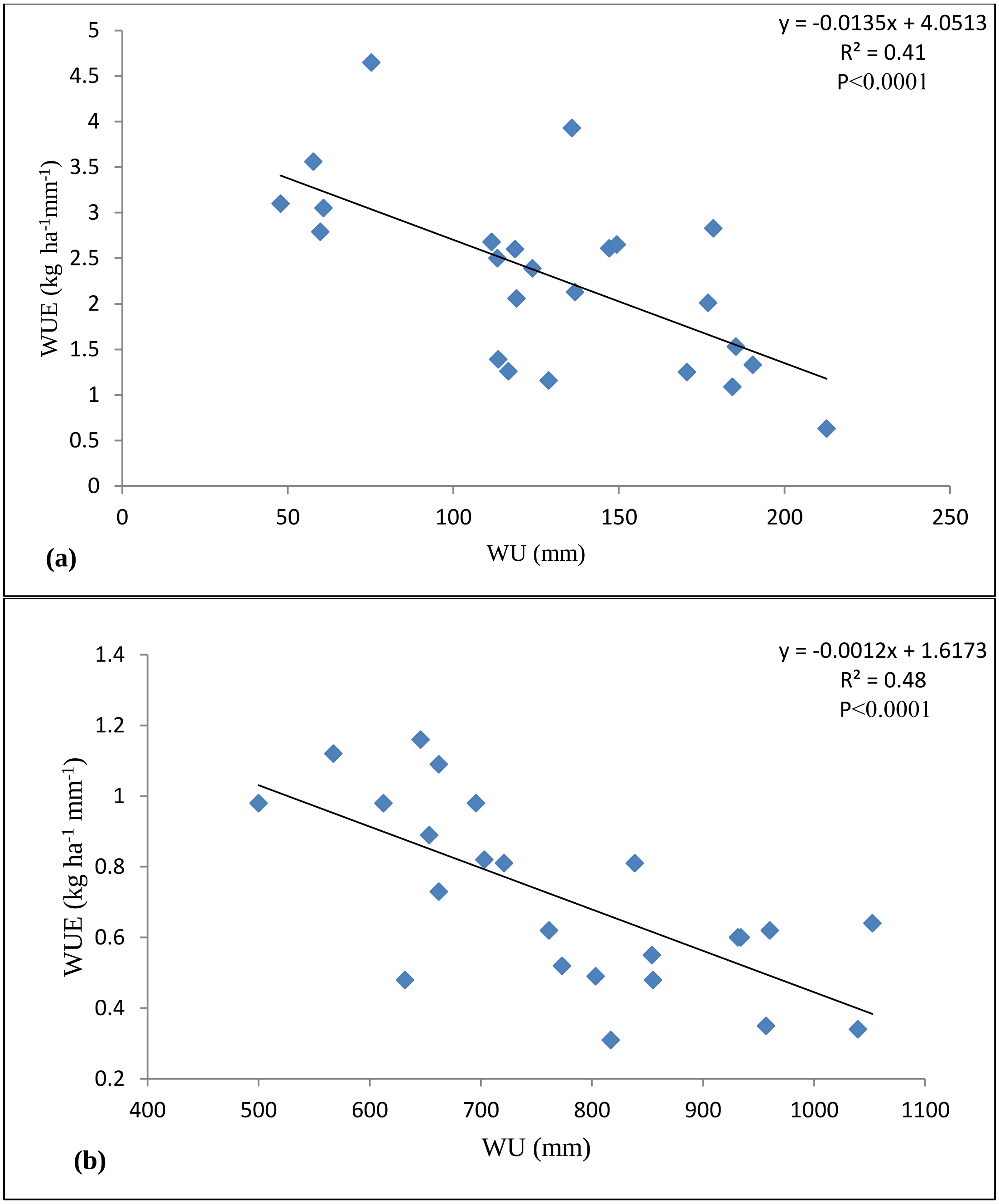


Figure 4.15: Relationship between Water Use Efficiency and Water Use (WU) under rainfed (a) and irrigated conditions (b) at Sebele.

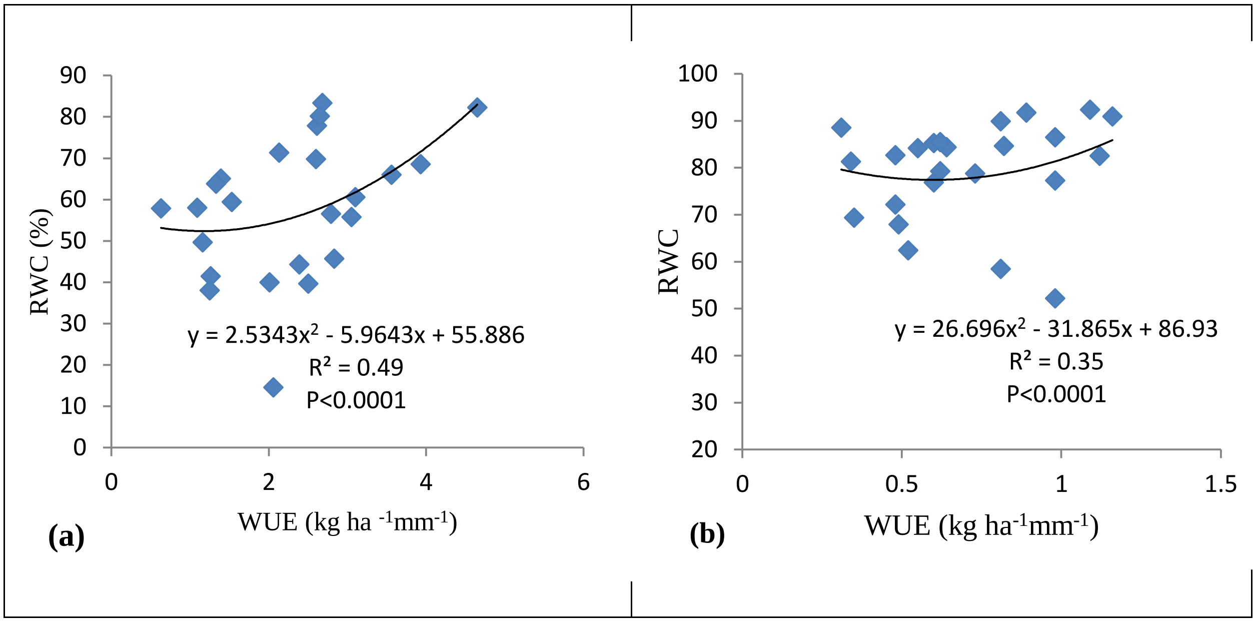


Figure 4.16: Relationship between Water use efficiency and Relative water content in rainfed (a) and irrigated conditions (b).

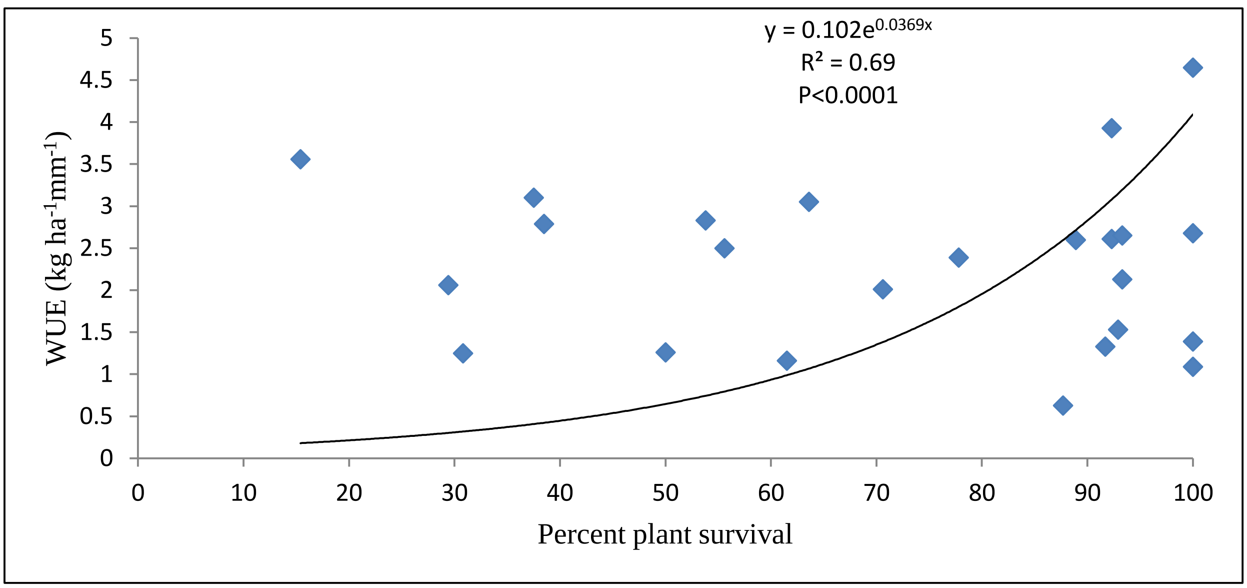


Figure 4.17: Relationship between Water use efficiency and percent plant survival under a rainfed condition.

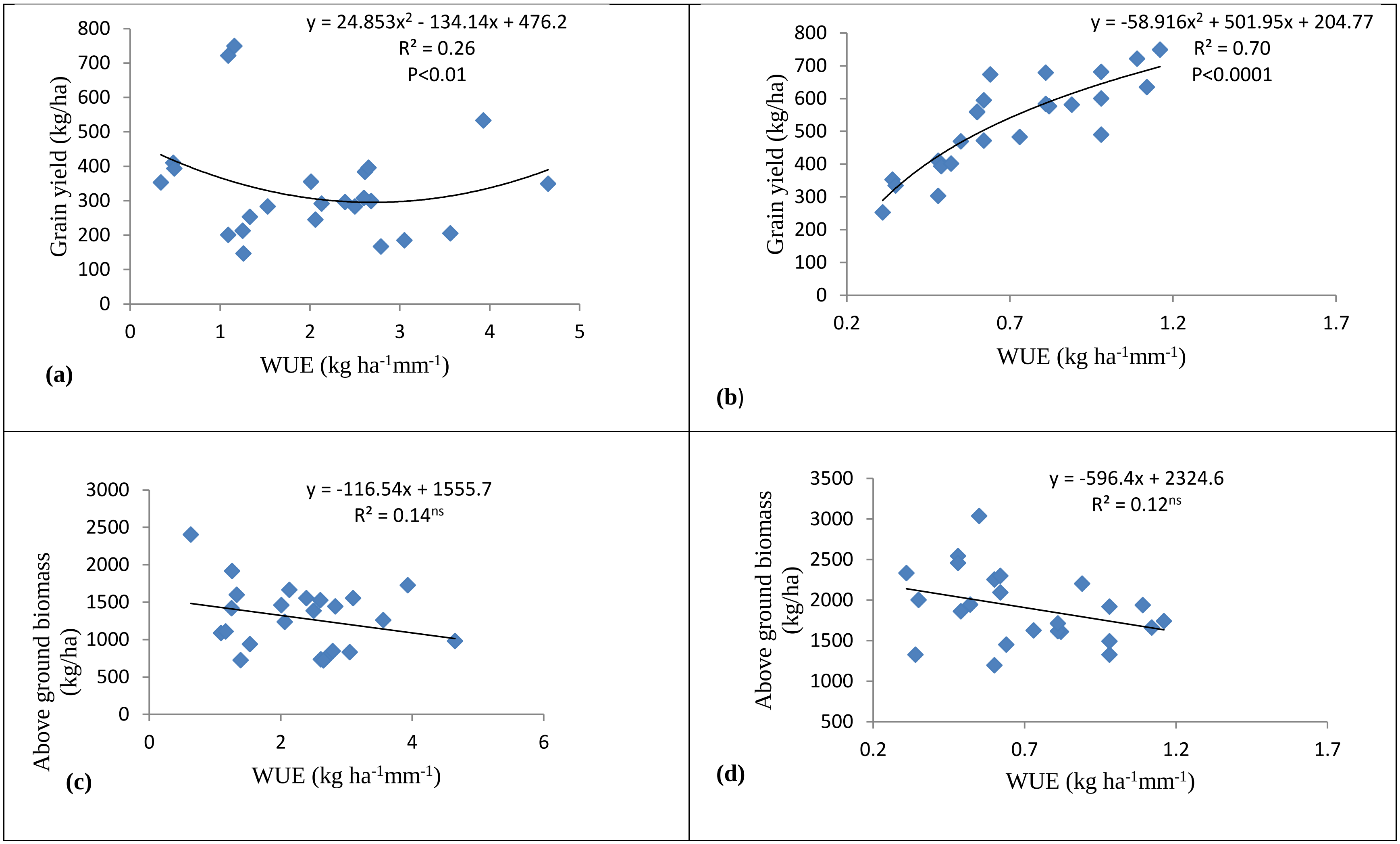


Figure 4.18: Relationship between Water use efficiency (WUE) and yield at Sebele.

Grain yield: rainfed (a), irrigated (b), Biomass yield: rainfed (c), irrigated (d)

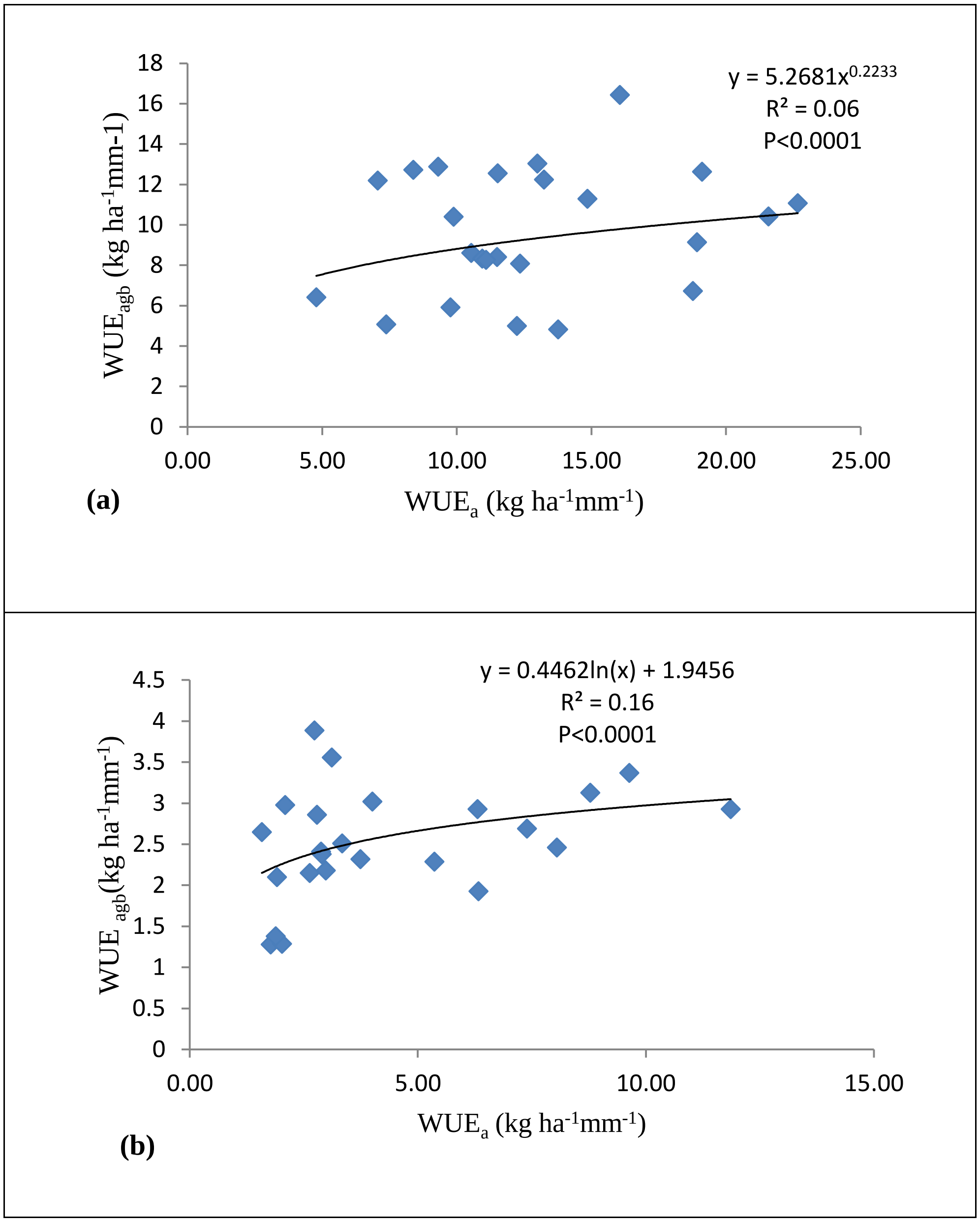


Figure 4.19: Relationship between anthesis water use efficiency (WUEa) and above ground biomass water use efficiency (WUEagb) under rainfed (a) and irrigated conditions (b) at Sebele.

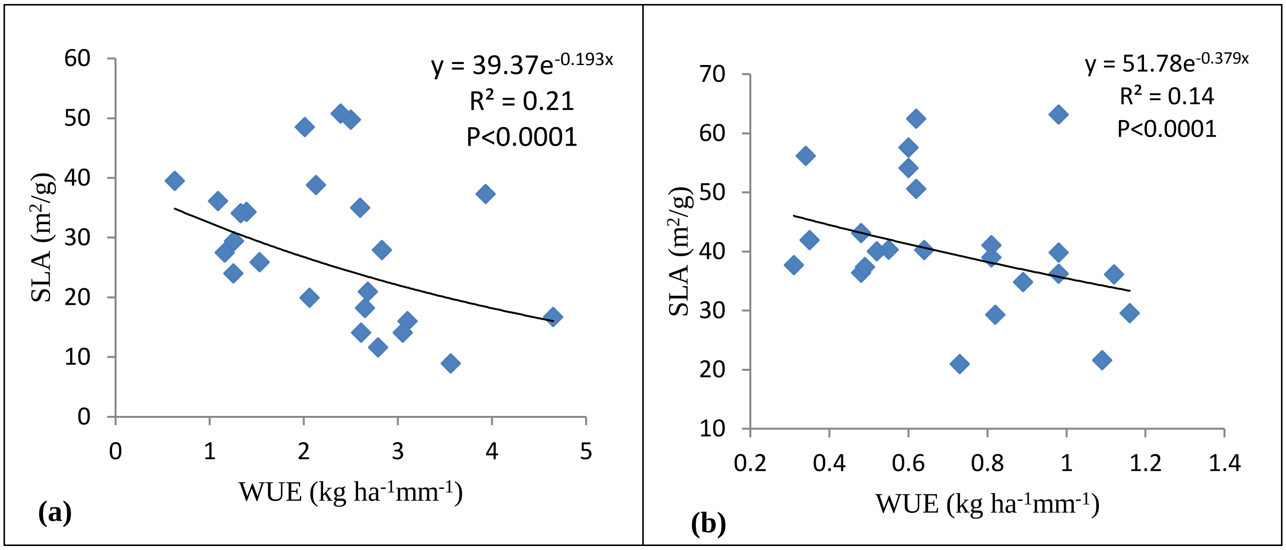


Figure 4.20: Relationship between Water use efficiency and Specific leaf area in rainfed (a) and irrigated (b) conditions at Sebele.

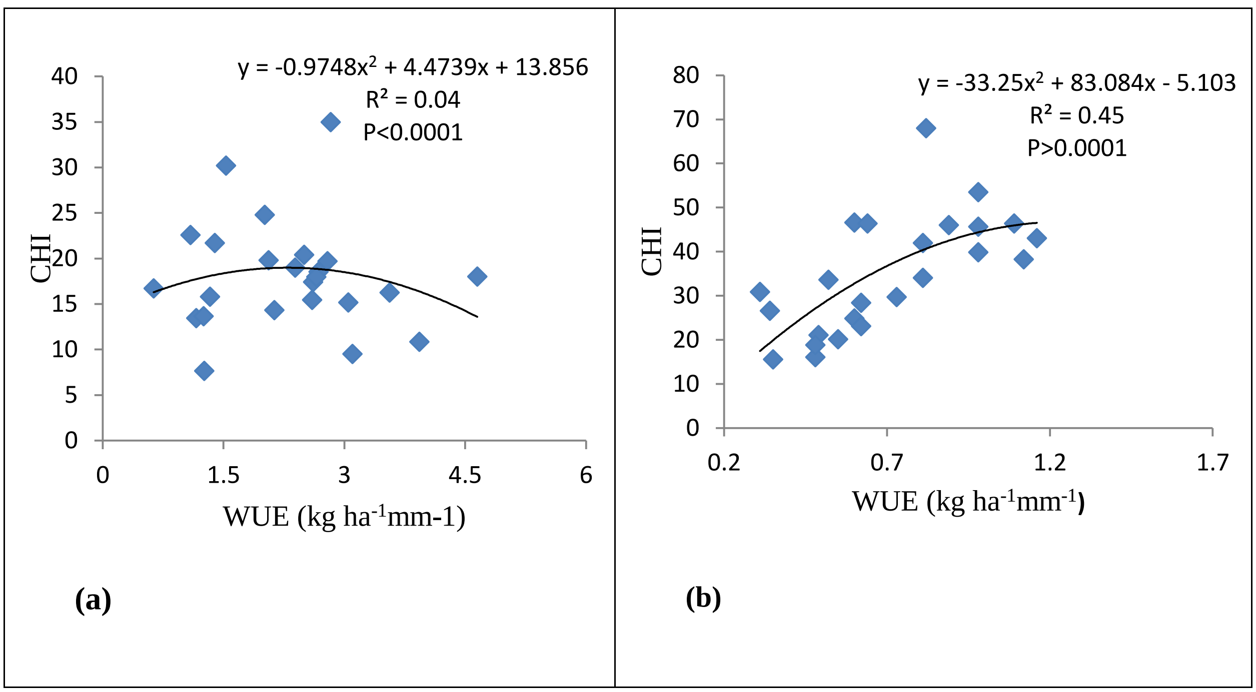


Figure 4.21: Relationship between Water use efficiency (WUE) and Crop harvest index (CHI) in rainfed (a) and irrigated (b) conditions at Sebele.

Table 4.6: Relationship between water use efficiency and plant traits under a water deficit condition

Plant trait	Equation	R^2
CHI	$y = -0.97x^2 + 4.47x + 13.86$	0.04
SLA(m^2/g)	$y = 39.37e^{-0.193x}$	0.21
RWC%	$y = 2.53x^2 - 5.96x + 55.88$	0.49
Percent plant survival	$y = 0.102e^{0.036x}$	0.69
Yield (kg/ha)	$y = 24.85x^2 - 134.14x + 476.2$	0.26
Above ground biomass (kg/ha)	$y = -116.54x + 1555.7$	0.14
Average		**0.31**

CHAPTER FIVE

DISCUSSION

Drought is one of the most important factors affecting plant growth, development, survival, and crop productivity posing a substantial threat to sustainable agriculture (IPCC, 2007). Cowpea is considered to be a drought resistant crop but failure of rainfall or lack of irrigation is a frequent cause of shortfall in production. When plants do not receive sufficient water they are subjected to a stress called water deficit and this causes a disruption in many cellular and whole plants functions, negatively affecting plant growth and reproduction (Adjinsakir *et al.*, 2013; Dodd and Ryan, 2016). This study was undertaken to investigate the effect of soil water deficit on water use efficiency of cowpea genotypes under field conditions. Both meteorological and soil characteristics data from the study sites indicates that the two sites presented almost similar agro-ecological zones for cowpea production, with soils prone to insufficient moisture for growth and development. This may explain the consistent and significant effect of water deficit on most parameters investigated in this study.

5.1 Decreased leaf area is an early adaptive response to water deficit

In this study the number of leaves per plant was significantly affected by water treatments. This caused a reduction in leaf number, leaf area, leaf area index and specific leaf area. According to Taiz and Zeiger (2002) water deficit reduces the water content of the plant, shrinking and relaxing the cell walls resulting in lower turgor pressure. Turgor reduction is the earliest significant biophysical effect of water stress and turgor dependent activities such as leaf expansion and root elongation are the most sensitive to water deficit (Dodd and Ryan, 2016).

BCA 001 and BCA 019 had the characteristics of a plant adapted to water limited environments showing low leaf areas under water deficit treatment. Supporting evidence indicating reduced leaf area due to water deficit in cowpea and Bambara groundnut were also reported (Hadi *et al*., 2012; Modi *et al.,* 2015). Additionally, Anyia and Herzog (2004) reported that under water deficit conditions, leaf area was significantly reduced as a result of leaf growth reduction and abscission. This leaf characteristic was believed to contribute to drought tolerance in other crops such as wheat (Lonbani and Arzani, 2011).

Samson and Helmut (2007) attributed the reduction in the number of leaves per plant under water stress to the reduction in cell division and cell enlargement. Since source strength depends on total leaf area, the reduction in leaf growth eventually reduces carbon supply (Taiz and Zeiger, 2002). Moreover, reduction in leaf area is a mechanism used by plants to avoid higher rate of transpiration and reduce surfaces for radiation due to water deficit (Hayatu, 2014). Although BCA 001 and BCA 019 had the lowest leaf areas under both water conditions this may also be attributed to their determinate growth habit; leaf number and area is associated with growth habit of the plant, determinate having less leaves per plant hence less area (Eman *et al*., 2014). In indeterminate growth habits, water stress limits not only leaf size but also leaf number because it decreases both the number and growth rate of branches but more reductions in determinate types. Leaf area is therefore important in drought tolerance selection because due to their plasticity an indeterminate genotype may have a semi determinate growth when exposed to drought hence having a significant reduction in leaf area.

As expected, specific leaf area (SLA) and leaf area index (LAI) were reduced due to a decrease in leaf area. The indeterminate genotypes had large SLA and LAI values largely due to their large leaf areas. Specific leaf area depends largely on leaf area therefore a leaf with more surface area could mean more SLA. New leaves according to Kearbuy (2004) have a greater SLA hence indeterminate crops “never stops growing” have high SLA as it was the case with BCA 002, BCA 016 and BCA 013. However, more leaf area does not indicate high drought resistance. An observation made by Veneklaas *et al.* (2002) showed that specific leaf area is reduced under drought conditions. The results of this study are also supported by Hayatu and Mukhtar (2010) and Pungulani (2014) who reported reductions in SLA due to moisture stress in cowpea. Additionally Painawadee *et al.* (2009) indicated that low SLA is preferable as it indicates higher drought resistance. Low SLA indicates thicker leaves and could be used as a surrogate trait for drought resistance because thicker leaves usually have a greater photosynthetic capacity (Songsri *et al.*, 2014). Genotypes BCA 001 and BCA 019 maintained consistency in having low SLA under rainfed and irrigated conditions. This consistency, according to Painawadee *et al.* (2009) makes SLA to be a selection criterion in drought resistance selection in such genotypes. On the other hand, leaf area index (LAI) was reduced by water deficit due to reduced leaf growth rate consequently leading to reduced leaf area. The decrease in LAI in the present study confirmed the previous findings of Nielsen and Nelson (2002) and Anyia and Herzog (2004) who observed significant LAI reductions under water stress in black beans and cowpea, respectively. Reduced LAI has previously been ascribed to reduction in photosynthesis and assimilate supply under water limited conditions which limits leaf expansion (Anjum *et al*., 2011).

Generally soil water deficit had a significant effect on leaf development as shown by reduction in leaf area, leaf area index and specific leaf area. The differences in the measured variables were also a result of variations in growth habit.

5.2 Water deficit affected plant phenological characters

An important plant response to water limited conditions is the timing and duration of key phenological events such as flowering (Blum, 2005). Cowpea exhibits a wide range of plant habits, flowering times and maturity (Ehlers and Hall, 1997).

It was expected that drought will also reduce the number of days to flowering and maturity, however the opposite was observed; irrigated plants flowered earlier than those grown under water deficit. BCA 001 and BCA 019 flowered and matured earlier than the rest of the genotypes. The results of the experiment are supported by Lawn (1982) who observed delayed flowering under water stress attributing this to extreme dehydration avoidance by the crop. Nonetheless this is contrary to Ahmed *et al.* (2008) regarding number of days to 50% flowering and maturity where plants modulate their development in response to unfavourable stress conditions by ending their life cycles earlier than those under normal or high soil moisture conditions. Abayomi and Abidoye (2009) attributed earliness as a way to achieve anthesis under drought conditions. Despite the contradictions, Muchow (1985) and Ahmed *et al.* (2008) concluded that water deficit may have little effect on days to flowering and maturity but more effect on the duration of flowering, hence in some genotypes it may be difficult to distinguish between possible effects of drought on the earliness or duration of flowering.

5.3 Water deficit reduces plant size

The growth of plants is highly influenced by water deficit occurring during development. Plants cope with limited water availability through reductions in plant size and surface area available for transpiration as a drought avoidance strategy (Mitchell *et al*., 1998). Canopy size represents surface area available for transpiration and plants cope with reduced water availability through reductions in canopy size; a dehydration avoidance mechanism (Mitchell *et al*., 1998).

The results show that plant height, canopy spread and stem diameter were significantly reduced by water deficit. The significant differences in varietal responses observed in plant height might be due to the varietal differences among the genotypes evaluated. Reductions in plant size due to water stress have been reported in cowpea, Pungulani (2014) and safflower (Canavar *et al*., 2014). Overall, BCA 001 and BCA 019 showed moderate decreases in vegetative components under water deficit conditions suggesting that the genotypes were able to strike a balance between minimizing water losses through transpiration while allowing biomass production to continue (Passioura, 2002). The decreased shoot growth may constitute an adaptive response to water deficit and may be attributed to the reduction in plant cell turgor which affected cell division and expansion. Cell division however has been reported to be less sensitive to water deficit than cell enlargement. The depression of plant height could also have resulted from a reduction in plant photosynthetic efficiency as reported by Sikuku *et al.* (2012).

The trend observed in the results showing lower canopy spread and height under limited water supply is consistent with reports by Mabhaudi (2012) who also observed reduced plant growth in Bambara groundnuts. Stem diameter is also among the traits that reduced significantly with water deficit; more reduction observed in BCA 001 and BCA 019. According to Omae *et al.* (2007) water stress reduced cowpea stem diameter by 32%. This is because under drought stress plant morphological features change to adapt to the extreme drought hence a reduction in stem diameter and generally plant size. The results of Omae *et al.* (2007) corroborated the findings of this research.

5.4 Maintenance of plant water status is an important trait under drought stress

Tolerance to internal water deficit has been emphasized as an important adaptation trait that contributes to drought tolerance (Sikuku *et al.,* 2012). Relative water content (RWC%) is therefore an appropriate measure of plant water status in terms of the physiological consequence of cellular water deficit. According to Reddy *et al.* (2003), RWC% for leguminous crops such as peanuts and cowpea is usually in the range of 30-100%, non stressed plants have a RWC in the range of 85-100%.

Results from this study indicated a significant depression of RWC% by water deficit. Most genotypes under water deficit condition had a RWC of above 60% with BCA 001 having the highest of 80%. BCA 001 maintained the highest RWC even under a water stressed condition indicating its ability to maintain plant water status. BCA 013 and BCA 016 were however the drought susceptible ones. Similar results of RWC% of cowpea at the range of 60 to 80% in a water stressed environment were reported by Lobato *et al*. (2008) whereas Anyia and Herzog (2004) recorded values between 75 and 92%.

It is well established that the decrease in relative water content is a result of lower water availability in the soil. This according to Kearbuy (2004) results in osmosis in the environment progressively becoming negative, causing many biochemical and physiological alterations aimed at decreasing plant water loss to the environment during transpiration to maintain metabolic function and adjust the species osmotically. Other sources have indicated the limitation of carbohydrates supply caused by water stress as one possible explanation for decreased RWC (Lawlor and Cornic, 2002).

Sikuku *et al.* (2012) when describing a legume with a higher leaf water status, stated that the crop should have an ability to absorb more water from the soil and control water loss through the stomata. Moreover, a crop which is able to maintain high RWC under moisture deficit would possibly maintain protoplast hydration for a large duration under water deficit stress conditions to ensure productivity (Vurayai *et al.,* 2011). Such crops also have the ability to efficiently use available water to give better yields (Anyia and Herzog, 2004). These characters describe the observations made in BCA 001 hence can be described as the most drought tolerant genotype.

A plant which maintain high RWC under water deficit is expected to be more drought tolerant as indicated by the percent survival results. Although BCA 001 and BCA 009 were the most drought tolerant, an interesting observation was made in BCA 009 in that it had delayed senescence. Such plants according to Gwathmey *et al.* (1992) maintain the green leaf area under drought stress and it is believed that the maintenance of green leaf area contributes to continued carbohydrate formation during drought and faster recovery following a rainfall event. Maintenance of high RWC was associated with drought tolerance in creeping bentgrass (McCann and Huang 2008); rice (Ambavaram *et al*., 2014) and potato (Soltys-Kalina *et al*., 2016). This may be due to morphological characteristics like development of deep root system and biochemical responses to drought leading to omostic adjustment. According to Ambavaram *et al.* (2014) rice genotypes that accumulated more glucose, fructose and sucrose had maintained high RWC and were more drought tolerant.

5.5 Reduction in above ground biomass was due to water deficit

Results of final above ground biomass showed that there was a trend of declining biomass under rainfed relative to irrigated conditions. Such a trend was consistent with the trend observed for other plant growth parameters. Reduction in above ground biomass was more pronounced in BCA 001 and BCA 019 while the least reduction was in BCA 009. The results obtained from BCA 001 and BCA 019 suggested that the effect of drought was severe to reduce photosynthesis by decreasing leaf area and stem growth reducing the ability of the crops to intercept solar radiation. This report is consistent with Prabhu and Shivaji (2000) who reported that the main effect of drought in the vegetative period was to reduce leaf area so that crops intercept less sunlight. The mechanism underlying drought tolerance strategy in BCA 009 seems to be related to their ability of osmotic adjustment. According to Turner (1986) osmotic adjustment, as a process of active accumulation of compatible osmolytes in plant cells exposed to water deficit, may enable a continuation of leaf elongation, though at reduced rates. This explains the least reduction in biomass of BCA 009 under rainfed system.

Generally, results obtained in this experiment were consistent with the findings of Anyia and Herzog (2004) who reported a reduction in the range of 11 to more than 40 percent in cowpea biomass production. They attributed this to the decline in leaf gas exchange, leaf area and decreased water use efficiency. The effect of drought on biomass production of cowpea was also reported by other researchers (Abayomi and Abidoye, 2009; Abdou *et al.,* 2013 and Pungulani, 2014)

5.6 Water deficit reduced grain yield

The ultimate objective of crop production is to get maximum grain yield with available resources. Seed yield in cowpea is determined by the product of three components which are number of pods per plant that reach maturity, the average number of seeds in each pod and mean dry weight of seeds (Richards *et al.*, 2002).

Results of this study showed that water deficit significantly contributed to the reduction in number of pods per plant, pod length and number of seeds per pod and ultimately grain yield. On average there was a 42% reduction in yield with BCA 009 having the lowest reduction (7%). However, BCA 001 and BCA 013 were the highest yielding under water deficit conditions. Results of lower yield under rainfed condition concur with other findings in literature. Reduction in the number of pods was reported by Abayomi and Abidoye (2009); Hayatu and Habibu (2014). They observed that with increasing reduction in soil moisture, the number of seeds is reduced and this may contribute to low yield in cowpea. Supporting their observation, Aguyoh *et al.* (2014) linked the reduction in pod mass to earlier senescence which affected pod filling hence explaining the observations made in this experiment. It is worth noting that low rainfall and high temperatures were experienced in February 2015 the period in which most genotypes were at the flowering stage. Such a condition according to Watanabe *et al.* (1998) contributes to the low number of pods per plant, abscission of flowers and pods resulting in low yield. Although the number of seeds per pod and pod length are genetically determined, the significant reductions observed in this study may be attributed to the effect of water deficit on seed filling as indicated by the presence of a large number of desiccated seeds in the water deficit treatments. Supporting evidence was reported by Pungulani (2014) who ascribed the reduction to the limitation in dry matter partitioning.

Overall, the results showed that among other cultivars, genotype BCA 009 which is a better survivor of drought had the highest number of pods and seed weight but lower yields under irrigated and rainfed conditions as compared to other genotypes. Although low yielding it had more yield stability and its yield reduction was lower than that of others under a water deficit condition. BCA 001, the most drought surviving genotype had the lowest number of pods, lowest seed weight and highest yield reduction compared to BCA 009 under water deficit condition. Nonetheless BCA 001 maintained the highest yield. With this contradicting observation, it is interesting to know if a stable, but rather low yielding genotype will be more water use efficient.

5.7 Harvest index was significantly reduced by water deficit

Harvest index indicates the fraction of dry matter allocated to seeds (Khonok *et al.,* 2015). Literature indicates that dry matter production and harvest index are positively correlated to yield Singh *et* al. (1997) and Varga *et al.* (2013), hence it was expected that a reduction in biomass and yield will lower harvest index under a rainfed condition.

The results of the study met the expectations both in crop harvest index and pod harvest index. Supporting these findings, Songsri *et al.* (2009) and Shinde *et al.* (2010) showed that drought led to a dramatic drop in the harvest index of peanuts. In cowpea Abayomi and Abidoye (2009) concluded that harvest index significantly decreased with increasing soil moisture stress.

5.8 High WUE is a result of low water use under a water deficit conditions

Water use was significantly low under rainfed conditions resulting in high water use efficiency (above ground biomass and yield). More reductions in terms of water use were visible in BCA 019 and BCA 016. However the high yielding BCA 001 was more water use efficient under rainfed conditions than BCA 019. Although the two genotypes did not vary much in most measured parameters, the lower yield of BCA 019 could be a due to its small seed size. Under irrigated conditions, genotypes with low water use like BCA 001 had the highest WUE.

Features linked to low yield under drought such as small plant size, short growth duration ascribe high WUE because they reduce water use (Kulathunga, 2013). It is evident that lower water use was the main drive for high water use efficiency under both rainfed and irrigated conditions. The observed reductions in canopy size, grain yield and high WUE due to water deficit agrees with the findings of Blum (2005). Similar results where low water use under drought stress resulted in high WUE were reported in beans and cowpea (De Costa and Ariyawansha, 1996; Anyia and Herzog, 2004). The findings of high water use efficiency for the irrigated plants with low water use are in agreement with Abdou *et al.* (2013) who attributed low water use to be the main determinant of WUE. Blum (2009) has indicated that genotypic variation in WUE under limited water is affected more by variation in the denominator (WU) rather than variation in the nominator (biomass or yield).

Above ground biomass water use efficiency at the anthesis stage was high for most genotypes and reduced at maturity stage. This according to Lobato *et al.* (2008), is due to large biomass at reproductive stage as compared to maturity stage where most leaves are lost. In addition De Costa and Ariwansha (1996) attributed high biomass WUE at anthesis to lower water use because at maturity stage water use throughout the growing season is used to calculate WUE. Supporting these results is Ahmed *et al.* (2011) who indicated that cowpeas were more water use efficient when drought was imposed at the reproductive stage than at maturity stage. Similar findings have also been reported in common bean (Calvache *et al.*, 1997). According to Blum (2009) water deficit during the reproductive phase of crop development is the most limiting factor hence it is essential for plants to efficiently use water at this stage irrespective of the quantity of the biomass quantity achieved at the vegetative phase (Kato *et al.*, 2008). This confirms the results obtained in BCA 001 and BCA 019 which had the highest anthesis WUE although they had the lowest biomass.

Although lower water use resulted in high water use efficiency at maturity under a rainfed condition, BCA 009 had the highest WUE despite it not being the lowest water user. However it was not significantly different from BCA 013, BCA 016 and BCA 002. BCA 009 has an indeterminate growth habit suggesting that variations in genotype response to WUE may be due to growth habit. Pungulani (2014) reported that biomass WUE is normally high for the spreading cowpea genotypes due to their large biomass. In this study, the difference between the two cowpea varieties in WUE was attributed to a lower biomass in the determinate variety while the indeterminate variety had more biomass resulting in high WUE; both genotypes had insignificant differences in water use. This however is in contrary to Hall (2004) whose findings indicated an increase in biomass WUE in the erect genotypes than the spreading ones. This according to Hall (2004) is due to a large amount of water used by the spreading varieties. In addition, a study by Cordon *et al.* (2002) reported that wheat genotypes experiencing higher water use efficiency at the well watered site realized a relatively poor biomass. This was the case in the irrigated BCA 001 which had the highest above ground biomass WUE although it did not have the highest biomass.

The results obtained in this study suggested that under water stress, greater grain yield was associated with lower water use while above ground biomass production was associated with moderate water use resulting in high water use efficiency values.

5.9 Rain use efficiency

The Hukuntsi experimental site which was characterized by the low but rather well distributed rainfall had highest grain yield rainfall use efficiencies as compared to WUE for rainfed genotypes in Sebele. This might be due to the distribution of rainfall which was more favourable during the reproductive stage resulting in more grain yield in Hukuntsi than Sebele. The differences in the climatic condition and soil properties might have attributed to the differences as reported by Kattge and Knorr (2007). Moreover Sinclar *et al.* (1984) mentioned that a geographical solution to increasing WUE can be related to crop production in those regions with warm climates with well distributed rainfall in which water use is reduced. Supporting evidence has also been given by Olalde *et al.* (2001) where water use efficiencies were high in an environment which had moderate temperature and erratic but normally distributed rainfall.

5.10 Relationship between water use efficiency and plant morphological traits, yield and its components.

Since water deficit resulted in survival of some genotypes and low values of “specific leaf area, harvest index, grain yield, above ground biomass and low water use”, the fundamental question was whether these observations could lead to higher water use efficiency in cowpea genotypes under a water limited condition.

In this study the highest grain yield and biomass was associated with moderate water use except for biomass under rainfed where biomass increased linearly with water use. The lower water use translated directly to high water use efficiency. According to Blum (2011) genotypes with low water use “as it was the case with BCA 001 and BCA 019” are able to extract more water from the soil whilst maintaining higher stomatal conductance will have high yield. Similar observations where low water use resulting in high yield in cowpea were made by Anyia and Herzog (2004); Abdou *et al.* (2013). Traits such as SLA and CHI increased linearly with water use although the relationship was weak. This was attributed to specific leaf areas and above ground biomass which were high in genotypes with high water use. Mabhaudi (2012) indicated that plants cope with drought stress by reducing the canopy size resulting in moderate water use. This agrees with the relationship of SLA and CHI with water use since they rely on leaf area and biomass.

The strong relationship of relative water content and plant survival to water use efficiency indicate that plant water status contributed more to the final water use efficiency. Varga *et al.* (2013) reported a stronger correlation between drought tolerance and water use efficiency in wheat under water deficit conditions. In contrast, Araus *et al.* (2003) reported the presence of a negative correlation between drought tolerance and water use efficiency in the case of limited water supply. However this study confirms the inference made by Varga *et al.* (2013).

It has been observed over many experiments that specific leaf area is closely and negatively correlated with water use efficiency in crops such as wheat and peanuts (Zhang *et al.,* 2007; Songsri *et al.*, 2013). In cowpea a very weak or no correlation has been found (Ismail and Hall, 1992; Araus *et al.,* 1997; Anyia and Herzog, 2004). In this study high SLA did not translate to high WUE as described by Anyia and Herzog (2004). Water use efficiency increased with decreasing specific leaf area under both water regimes although the relationship was weak.

Kang *et al.* (2013) found that water use efficiency increased linearly with harvest index. When water supplies were with-held, increasing values of harvest index resulted in better WUE in wheat but after reaching the peak, WUE drastically reduced. Similar results in cowpea were reported by Pungulani (2014) hence they confirm the findings of this study.

Regarding the relationship between WUE and grain yield, under rainfed condition there was a very weak correlation between the two. However under irrigated conditions, WUE had a strong linear relationship with grain yield. The WUE value for the highest yield obtained was four times less than the highest WUE value under rainfed system. That is for the same WUE of 1.2kg $ha^{-1}mm^{-1}$ which was used to obtain 749kg of grain yield under irrigated condition, 200kg was obtained in rainfed system. This shows that water use efficiency was therefore not necessarily responsible for increased grain yield. It was concluded by Varga *et al.* (2013) that as previously suggested by Passioura (1996) water use, water use efficiency are drivers of yield. Blum (2005) while agreeing that water use and harvest index are drivers of yield, stated that WUE was just a passenger. The increase in water use efficiency was attributed to reduced water use rather than a net improvement in plant production (Blum, 2009). The almost parallel relationship between grain yield and WUE under rainfed conditions are verified by the cited findings. Despite the reviews by Blum, (2005) and Blum (2009) positively significant correlations between WUE and grain yield or biomass under water stressed condition have been reported in cowpea (Shamsi *et al.*, 2010; Pungulani, 2014) and wheat (Shirazi *et al.*, 2014).

For above ground biomass water use efficiency at anthesis and maturity, the relationship was positively linear and weak. Final above ground biomass water use efficiency increased with increasing anthesis WUE although the final WUE was lower. A similar trend was reported by Shouse *et al.* (1981); Ahmed and Suliman (2010). Nevertheless WUE at maturity did not strongly relate to biomass production; the lower water use efficient genotypes tended to be the ones that produced large biomass even though they used more water. The association was negative signifying that highest water use efficiency was associated with lower water use efficiency regardless of the watering condition. The results are comparable to those obtained in soybean by Visser (2014) while contrary findings have also been reported by Abdou *et al.* (2013).

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Water deficit had a significant effect on all cowpea growth attributes measured in this study. Genotype BCA 009 had lower reductions in most variables and a stable yield. Cowpea was more water use efficient under water deficit conditions. Genotypic variations in cowpea with response to water use efficiency under water deficit conditions were observed. This was mainly due to their relatively lower water use and growth habit. Features linked to lower yield under drought such as small plant size resulted in low water use. Above ground biomass water use efficiency varied with cowpea developmental stages; water use efficiency was high at anthesis and reduced with maturity. As a result of high above ground biomass, indeterminate cowpea genotypes had high total biomass water use efficiencies at maturity with BCA 009 recording the highest. However for grain yield water use efficiency, determinate cowpea genotypes "BCA 001 and BCA 019" had the highest water use efficiencies irrespective of the geographical location. The main drive for high water use efficiency was lower water use and plant water status instead of grain yield as supported by the strong relationship with water use. Selection for high yield under water deficit conditions should therefore be based on lower water use than high water use efficiency. Genotype BCA 009 with its delayed leaf senescence, yield stability and drought tolerance is suitable for drought tolerance breeding programmes and improvement in water use efficiency.

6.2 Recommendations

- Determinate cowpea genotypes with short duration to maturity are recommended for use under water deficit conditions due to their low water use.
- Further studies on cowpea at molecular level needed to understand mechanisms responsible for high water use efficiency under water deficit condition.
- Based on their performance, BCA 001 and BCA 019 are recommended for use as a source for development of high grain yield and low water use varieties.
- To confirm genotypic variations in water use efficiency, surrogate traits which have been proven to correlate with water use efficiency such as carbon isotope discrimination are recommended.

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APPENDIX

Table 1: Table of means for cowpea morphological characteristics

*** indicates significant difference at P<0.0001

Parameter	Days to flowering	Days to maturity	Plant height (cm)		Canopy spread (cm)	
Mean	55	99	53.54		167.21	
CV (%)	5.3	7.6	11.7		21	
LSD(P≤0.05)	1.68	4.4	6.05		20.59	
Genotype (G)	***	****	***	****	***	****
Water (W)	***	***	***	***	***	***
G*W	***	***	***	***	***	***

Table 2: Table of means for Relative water content (%)

Parameter	RWC (%)
Mean	68.7
CV (%)	9.6
LSD (P≤0.05)	3.85
Genotypes	***
Water	***
G*W	***

*** indicates significant difference at P<0.0001

Table 3:Table of means for cowpea yield components

******* indicates significant difference at (P<0.0001) and ns non significance

Parameter	Number of pods/plant	Pod length (cm)	Number of seeds/pod
Mean	65	15.41	12
CV (%)	23.8	9.57	11.57
LSD (P≤0.05)	9.07	3.85	0.80
Genotype (G)	***	***	***
Water (W)	***	***	***
G*W	***	***	ns

Table 4: Table of means for above ground biomass and grain yield of cowpea

Parameter	Biomass (kg/ha)	Yield (kg/ha)
Mean	1553	488.5
CV (%)	17.1	24.7
LSD(P≤0.05)	159.48	57.6
Genotypes	***	***
Water	***	***
G*W	***	***

*** indicates significant difference at P<0.0001

Table 5:Table of means for above ground biomass and grain yield WUE of cowpea under irrigated and rainfed conditions

Parameter	Biomass (kg $ha^{-1}mm^{-1}$)	Yield (kg $ha^{-1}mm^{-1}$)
Mean	6.11	1.5
CV (%)	30.36	35.86
LSD(P≤0.05)	1.09	1.09
Genotypes	***	***
Water	***	***
G*W	***	***

*** indicates significant difference at P<0.0001

Table 6: Characteristics of the six genotypes selected for study

Parameter	Code	Source	Growth habit
Blackeye[a]	BCA 001	NPGRC	Determinate
Tswana cream[a]	BCA 013	NPGCR	Semi-determinate
Speckled Grey[b]	BCA 019	Lecheng	Determinate
Speckled Grey[b]	BCA 002	Hukuntsi	Determinate
Tswana Brown[b]	BCA 009	Hukuntsi	Indeterminate
Speckled Brown[b]	BCA 016	Lecheng	Indeterminate

[a]Released variety, [b]Landrace