DETERMINING WATER USE OF INDIGENOUS GRAIN AND LEGUME FOOD CROPS

AT Modi and T Mabhaudhi

WATER RESEARCH COMMISSION

TT 710/17

DETERMINING WATER USE OF INDIGENOUS GRAIN AND LEGUME FOOD CROPS

Report to the

WATER RESEARCH COMMISSION

by

Modi, A.T. and Mabhaudhi, T.

Crop Science, School of Agricultural, Earth & Environmental Sciences
University of KwaZulu-Natal

WRC Report No. TT 710/17
ISBN 978-1-4312-0887-6

April 2017

Obtainable from

Water Research Commission

Private Bag X03

Gezina, 0031

orders@wrc.og.za or download from www.wrc.org.za

The publication of this report emanates from a project titled *Determining water use of indigenous grain and legume food crops* (K5/2274).

Printed in the Republic of South Africa

EXECUTIVE SUMMARY

Interest and research on indigenous food crops has been steadily increasing in South Africa and elsewhere. This has been driven by realisations of increasing water scarcity, growing populations and increasing food and nutrition insecurity among the rural poor. Climate variability and change, which has a multiplier effect on several of these drivers, has added to the growing interest in indigenous food crops. Most of the current major food crops may not be able to meet projected future food demand under predicted climate change. Thus, there is a need to come up with innovative strategies that will broaden the current food basket and possibly contribute to future food security in South Africa. It is in this regard that indigenous food crops are being proposed as reasonable alternatives under water limited conditions.

Owing to the fact that cereal and legume crops play an important role in the dietary provisions of South Africans, the Water Research Commission of South Africa commissioned the current project with the aim to quantify and predict water use of selected indigenous legume and grain crops for sustainable rainfed food production in South Africa. The specific objectives were to (i) review available literature to select and motivate indigenous legume and grain food crops for the study; (ii) measure the range of water use of selected crops as sole crops and intercropping under known environmental conditions; (iii) model water use and agronomic management of selected crops as sole crops and intercropping for extrapolation to fit a range of agro-ecological zones suitable for rain-fed farming; and (iv) formulate recommendations for best management practices on water use of indigenous grain and legume food crops.

Consistent with the set objectives for the study, the methodology adopted for the study involved conducting several quantitative and systematic reviews focussed on indigenous cereals and grain legumes. These reviews formed the basis for much of the crop selection. Separate to the reviews, conventional field trials and modelling experiments were used to address objectives related to measurement of crop water use, crop modelling and development of best management practices. Field trials were designed to quantify water use in sole crops as well as intercrops involving indigenous cereal and grain legumes. While the focus of the study was on indigenous cereal and legume food crops, major cereals and legumes were also considered, albeit to a limited extent and for benchmarking purposes only. Overall, the range of crops that were studied during the project included maize landraces (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), bambara groundnut (*Vigna subterranea* L.), cowpea (*Vigna unguiculata*), dry bean (*Phaseolus vulgaris* L.) and groundnuts (*Arachis hypogea* L.).

The review of cereals showed that there was a wide range of African indigenous cereal crops that were nutritious and suited to rainfed conditions. Of these, the review noted that sorghum had a comparative advantage under rainfed conditions due to its relatively high WUE, drought, heat and aeration stress tolerance, high germplasm variability, comparative nutritional value, and existing food value chains. Currently, sorghum production was low as maize tended to occupy ecological niches that were suited to its production. This had a carry-over effect on the entire value chain. With respect to legumes, the review highlighted that grain legumes were rich sources of proteins and micronutrients with dual purposed (human and animal consumption) thus making them ideal for crop-livestock systems that are typical of the semi- and arid tropics. While legumes showed large diversity and adaptability to the widest range of environments, current research and development had only focussed on a few major legumes to the detriment of minor grain legumes, which are indigenous to Africa and more adaptable to water-limited conditions.

Results of field trials for sole crops confirmed the major findings of the literature reviews. Under rainfed field conditions, sorghum showed adaptation to low water availability mainly through physiological and phenological plasticity. Sorghum landraces performed statistically similar to hybrid and open-pollinated varieties confirming the potential of indigenous landraces that are currently used by rural farmers. With respect to grain legumes, a comparative study of selected major and minor (indigenous) grain legumes species showed that while indigenous grain legumes performed well and showed adaptation to low water availability, they were generally out-performed by major grain legumes. This was mainly attributed to the fact that major grain legumes have been the subject of much crop improvement, while minor grain legumes have not. Despite this, bambara groundnut emerged as an African indigenous legume with potential for further crop improvement.

The study assessed two intercropping scenarios, a sorghum-cowpea-bottle gourd and a maize landraces-bambara groundnut-dry bean intercrop. The focus was on cereal-legume intercrops that featured indigenous cereal and grain legumes. Intercropping sorghum with cowpea and bottle gourd or maize landraces with either dry bean or bambara groundnuts did not have a negative effect on growth and yield of both sorghum and maize landraces. Under limited water availability, intercropping resulted in more of a facilitative than competitive interaction. Under rainfed conditions, intercropping improved overall productivity of sorghum and maize landraces translating to improvements in water use (WU), land use efficiency (LER) and water use efficiency (WUE). Overall, intercropping resulted in improved soil water availability as the legumes acted as a live mulch hence minimising unproductive losses to soil evaporation. Thus, under rainfed conditions, intercropping cereals and legumes would be beneficial in terms of improving resource use efficiencies (land, water and solar radiation). Intercropping also offers long-term benefits in terms of sustainability through the legumes' ability to fix nitrogen. However, the benefits of nitrogen fixed by the legumes to the current or subsequent cereal crop require further investigation.

A major aspect of the current study was to model the selected indigenous cereal and legume food crops for extrapolation to other rainfed ecologies in South Africa. Two models were selected for this purpose – AquaCrop and APSIM. The two crop models are uniquely different, with AquaCrop being a simple water-driven model while APSIM is a complex radiation-driven model. AquaCrop was therefore used to model sole crops while APSIM was applied for the intercrop for which it was most suited. For the sole crop, AquaCrop modelling focussed primarily on sorghum since millets and bambara groundnut were previously modelled as part of WRC Project No. K5/1771//4. With respect to modelling sorghum, AquaCrop could simulate canopy cover, biomass accumulation, harvest index and yield relatively well for all sorghum genotypes and different environments. With respect to intercropping, the APSIM model could simulate the sorghum–cowpea intercrop system under different water regimes. The model gave reliable simulations of phenology, biomass, yield and crop water use for both sorghum and cowpea under the different water regimes.

Following calibration and validation of the crop models, a secondary objective was to then apply the models for scenario analyses to develop best management practices. AquaCrop was applied for a range of agro–ecologies across KwaZulu–Natal to assist with generating best practice management recommendations for cultivar choice and planting date selection. Similarly, APSIM was also used to assess different management scenarios for selected areas in KwaZulu-Natal and to develop best management practices for improving water use efficiency under intercropping. Major recommendations that were developed included cultivar selection, selection of suitable planting dates, use of rainwater harvesting to increase water availability, use of mulches to minimise soil evaporation and increasing plant populations in favourable agro-ecologies. In terms of agricultural water management, deficit irrigation was recommended for areas that had access to water for supplementary irrigation. However, proper irrigation scheduling is a prerequisite to achieving improvements in yield and WUE.

In conclusion, the current project succeeded in quantifying water use of indigenous cereal and legume food crops under varying environments. While the extrapolation to other rainfed agro-ecologies was limited to KwaZulu-Natal, due to availability of reliable data, the framework developed can be applied for a range of environments given that soil and climate data are available. The study provides a strong case for the promotion of underutilised, indigenous and traditional cereal and legume grain crops, especially in semi-arid environments. Underutilised indigenous cereal and legume food crops have potential role to contribute to crop production under climate variability and change as well as to food and nutrition insecurity in semi-arid regions. However, a major limitation to their production relates to the low potential and attainable yields of these crops, in particular minor grain legumes. This requires targeted efforts at crop improvement to improve their yields. In the short to medium term, the use of best management practices that include intercropping, appropriate cultivar and planting date selection as well as rainwater harvesting and conservation techniques have potential to improve current yields and improve water use efficiency under rainfed conditions. The use of crop models, and the ongoing work to model underutilised indigenous crops, should be commended and furthered. This is because crop models are useful in assisting to determine the yield and water productivity as well as suitability of production of underutilised indigenous crops under different management and biophysical scenarios.

Future research should focus on a few grain and legume food crops such as sorghum, bambara groundnut and cowpea, which have potential under rainfed conditions. Research should further explore developing value chains for these exemplar indigenous cereal and legume food crops. In addition, future research should also consider mapping South Africa to identify areas that would be suitable for the production of indigenous cereal and legume food crops.

ACKNOWLEDGEMENTS

The Project Team would like to extend their heartfelt gratitude to the following individuals, institutions and communities who assisted in the conduct of this project:

- The Water Research Commission for initiating, managing and funding this directed project.
- The University of KwaZulu-Natal for hosting and supporting the project.
- The farmers in Umbumbulu and Swayimane for making land available for the study.
- Dr Gerhard Backeberg and Dr Sylvester Mpandeli of the WRC for their leadership and guidance during the conduct of this project.
- The **Reference Group Members:**
  - Dr GR Backeberg — Water Research Commission
  - Dr NS Mpandeli — Water Research Commission (Chairman)
  - Prof JG Annandale — University of Pretoria
  - Dr C Mutengwa — University of Fort Hare
  - Dr GM Ceronio — University of Free State
  - Prof KK Ayisi — University of Limpopo
  - Mr T Ramashala — Department of Agriculture, Forestry and Fisheries
  - Dr YG Beletse — Agricultural Research Council
  - Dr M Fessehazion — Agricultural Research Council
- The **Project Team**:
  - Prof Albert T. Modi — UKZN (Project Leader)
  - Dr Tafadzwa Mabhaudhi — UKZN (Principal Researcher)
- The students at MSc and PhD levels registered at the Universities of KwaZulu-Natal who worked on various aspects of the project.
- The administration, technical and field support staff at the University of KwaZulu-Natal who supported the project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

ARC-ISCW	Agricultural Research Council – Institute for Soil, Climate and Water
ANOVA	Analysis of variance
CC	Canopy cover
CCI	Chlorophyll content index
DAP	Days after Planting
DAFF	Department of Agriculture, Forestry and Fisheries
FAO	Food and Agriculture Organisation
GDD	Growing degree-days
HI	Harvest index
KZN	KwaZulu-Natal
LAI	Leaf Area Index
LSD	Least significant difference
RMSE	Root mean square error
RSA	Republic of South Africa
RUE	Radiation use efficiency
SC	Stomatal Conductance
SWC	Soil water content
PAR	Photosynthetically active radiation
UKZN	University of KwaZulu-Natal
WAP	Weeks after Planting
WRC	Water Research Commission

LIST OF SYMBOLS

Roman (upper)

B	Final biomass (kg)
BD	Bulk density (g cm^{-3})
D	Drainage below the bottom of the root zone (mm)
Es	Soil evaporation (mm)
ET	Actual evapotranspiration or total evaporation (mm or m^{-3})
ET_a	Actual evapotranspiration (mm)
ET_c	Crop water requirement (mm)
ET_o	Reference crop evaporation (mm d^{-1} or mm h^{-1})
FC	Field capacity (m m^{-1} or vol %)
HI	Harvest index
I	Irrigation (mm)
K_c	Crop coefficient for standard (i.e. non-stressed) conditions
K_{c_adj}	Adjusted crop coefficient for stressed conditions
K_{sat}	Saturated hydraulic conductivity (mm h^{-1} or mm day^{-1})
P	Precipitation or rainfall (mm)
PWP	Permanent wilting point (m m^{-1} or vol %)
R	Runoff (mm)
RH	Relative humidity (%)
R_n	Net irradiance (W m^{-2} or MJ m^{-2} d^{-1})
SAT	Saturation (m m^{-1} (or vol %)
TAW	Total available water (m m^{-1} or vol %)
T	Air temperature (°C)
T_{ave}	Daily averaged air temperature (°C)
T_{bse}	Base temperature (°C)
T_{max}	Daily maximum air temperature (°C)
T_{min}	Daily minimum air temperature (°C)
T_{upp}	Cut–off temperature (°C)
WUE	Water use efficiency (kg mm^{-1} or kg m^{-3})
WP	Water productivity (kg m^{-3})
Y	Crop yield (kg or t ha^{-1} or kg ha^{-1})

Greek

ΔSWC	Change in soil water storage (mm)
θ_g	Gravimetric water content (g g^{-1} or %)
θ_v	Volumetric water content (cm^3 cm^{-3} or m^3 m^{-3} or m m^{-1})

REPOSITORY OF DATA

For details related to the project data, please contact:

Dr Tafadzwa Mabhaudhi (Principal Researcher)
Crop Science
School of Agricultural, Earth and Environmental Sciences
University of KwaZulu-Natal
Private Bag X01, Scottsville 3209
Pietermaritzburg, South Africa

CHAPTER 1

DETERMINING WATER USE OF INDIGENOUS GRAIN AND LEGUME FOOD CROPS: A REVIEW

Mabhaudhi, T. and Modi, A.T.

1.1 General Introduction and Conceptualisation

South Africa is a water stressed country with about 90% of it being classified as arid to semi-arid (RSA, 1998; DWAF, 2006). Under these conditions, water is the main factor limiting agricultural production. Based on this, water as a resource is scarce. In addition, drought is a common phenomenon, especially in rural South Africa where the majority of the population reside. Due to climate change, the frequency and intensity of droughts is predicted to increase in southern Africa (Schulze, 2011). Furthermore, it has been projected that by 2050 the demand for water for agriculture will increase due to expected growth in human population, expansion of competing industries (mining, energy and food processing), and reduced arable land and precipitation. Global population is currently sitting at about 7 billion while recent figures suggest that South Africa's population has passed the 50 million mark (UNFP, 2011). Considering this, research needs to come up with innovative/novel sustainable strategies that will promote the most productive use of the dwindling resource, at the same time improving food security for present and future South Africans. Within the scope of this review, this includes conducting research on water use of indigenous grain and legume food crops

The complexity of the water-energy-food security debate requires that South Africa come up with innovative mitigation strategies. The importance of such strategies should also base on an understanding and general acceptance that the combination of predicted climate change and increasing population growth pose a challenge to future food security for countries like South Africa that already have scarce water resources (RSA, 1998). As such, there is a need for research that will contribute to food security; such research will have to occur within the context of rural development because it is the people in these areas that are most vulnerable to climate change. Since climate change predictions indicate that most of the major crops currently in production will not be suitable (Baye et al., 2001), there is a need to explore alternative crops – future crops – that can be used to broaden the current food basket (Mabhaudhi, 2009), in the short-term, as well as to ensure future food security – long-term. This has led to previously neglected and underutilised species/crops (NUS) being touted as possible future crops. Local traditional and indigenous crops also belong to this category of crops – NUS (Mabhaudhi, 2012). Of interest to this current solicited project are indigenous legume and cereal food crops. These include Bambara groundnut (*Vigna subterannea* L. Verdc), cowpea (*Vigna unguiculata*), maize landraces (*Zea mays* L.) and grain sorghum (*Sorghum bicolor* L.).

A review of the literature and comparison with more conventional legumes and cereals such as dry bean, soybean, maize and wheat, showed that there is clear evidence of scant information describing water use of indigenous legume and cereal food crops. This is possibly because in the past, these crops have been overlooked/neglected by researchers, farmers and policy makers in favour of major legume and cereal crops. However, there has now been renewed efforts, spearheaded by the Water Research Commission (WRC) of South Africa as well as the Department of Science and Technology to study these crops (Modi and Mabhaudhi, 2013); this project is one such initiative by the WRC to initiate a project that will contribute to ongoing efforts on re-establishing traditional crops. However, to date, most of these efforts have been mimicking the approaches used to study the major crops (Mabhaudhi and Modi, 2013). There is also a need to study indigenous food crops within the context of the traditional cropping systems in which they were preserved. These historical cropping systems, such as intercropping, are thought to have been resilient and may therefore offer a solution to possible adaptation to climate change (Mabhaudhi and Modi, 2013). Intercropping is said to have benefits such as increasing crop diversity, strengthening household food security and improving sustainability of agriculture (Mabhaudhi and Modi, 2013).

A large proportion (90%) of the world's food energy is said to be derived from a mere 20 species, with wheat, maize and rice accounting for 60% of man's diet (Collins and Hawtin, 1999). Astonishingly, there are well over 7 000 partly– and fully–domesticated species that are known to be used as food (Thrupp, 2000; Williams and Haq, 2002). Thus, thousands of edible plant species remain relatively "underutilised", with respect to their ability to contribute to food security. Unlocking the potential of these crops through well-coordinated research, as has been done for the major crops, could be key to guaranteeing future security. The reduction in genetic diversity that historically and traditionally underpinned agriculture has led to the displacement of indigenous grain and legume food crops by more favoured major crops (Azam-Ali, 2010) such as dry bean, soybean, maize hybrids and wheat. Unlike the major crops that overtook them, indigenous food crops are often well adapted to local growing conditions (Padulosi, 1998), which are often marginal and harsh, thus offering sustainable food production (Idowu, 2009).

While the water use characteristics of major cereal and legume crops have been studied in detail and are well documented, the opposite is true for indigenous cereal and legume food crops. It is therefore imperative to conduct quantitative research on local indigenous food crops using both conventional and modern research approaches such as crop modelling in order to determine their water use. This research needs to also consider the cropping systems such as intercropping that have preserved these indigenous crops and quantify water use of indigenous crops under such scenarios.

1.2 Objectives

The contractually specified objectives of the project were:

1.2.1 General objective

To quantify and predict water use of selected indigenous legume and grain crops for sustainable rain-fed food production in South Africa

1.2.2 Specific objectives

i. To review available knowledge, select and motivate indigenous legume and grain crops for this research with reference to amongst others

- Water use
- Crop modelling
- Nutritional value
- Crop genetic diversity
- Cropping systems

- Local relevance

ii. To measure the range of water use of selected crops as sole crops and intercropping under known environmental conditions.

iii. To model water use and agronomic management of selected crops as sole crops and intercropping for extrapolation to fit a range of agro-ecological zones suitable for rain-fed farming

iv. To formulate recommendations for best management practices on water use of indigenous grain and legume food crops

1.3 Scope of the Report

The report is written in a series of self-contained chapters, with different authors. Each Chapter addresses at least one of the specific objectives of the project as set out in the terms of reference. Due to the paper format that has been used, the report does not have a general methodology section; each Chapter has its own specific methodology. In some cases, this may have inadvertently created cases of minor repetition, especially in the methodology section.

The report is structured to address the project objectives of the study in a logical framework. Chapters 1-3 address the first object related to conducting literature reviews. Chapters 4-7 report on field trials conducted to quantify water use of indigenous cereal and legume food crops as sole crops and intercrops; these address the second objective of the study. Chapters 8 and 9 address the third objective related modelling water use of indigenous cereal and legume food crops. Lastly, Chapters 10 and 11 address both objective three and four on agronomic management and developing best practice recommendations. A general overview of the report is provided below:

Chapter 1: provides a general introduction, background and conceptualisation of the entire study. It provides a motivation for the broad study as set out in the terms of reference. It also sets out the project's aims and specific objects as defined in the contract.

Chapter 2: is a literature review. It focusses on cereal crops, with a focus on sub-Saharan Africa and South Africa. It addresses the first objective of the study and provides an overview on underutilised cereal crops, their water use and potential. It also provides a justification for the use of sorghum in subsequent studies.

Chapter 3: is similar to Chapter 2 but focusses on legumes. It speaks to the need to promote research along the entire value chain as a strategy for promoting underutilised legumes. It also provides a motivation for the choice of legumes that form the basis of subsequent field studies in the study.

Chapter 4: reports on field trials to determine the water use of sorghum genotypes. The trial includes a hybrid, an open-pollinated variety and a sorghum landrace. Farmers typically use landraces and open-pollinated varieties, which allow them to recycle seed. The objective of this study was to provide comparative analyses of water use for the three sorghum genotypes under rainfed conditions.

Chapter 5: follows from Chapter 3 and reports on field trials evaluating water use of selected legumes. Four legumes were selected based on recommendations from the literature review (***cf.*** Chapter 3). These were split between major (dry beans and groundnuts) and minor/indigenous (bambara groundnut and cowpea) legumes.

Chapter 6: reports on field trials conducted to quantify of indigenous cereal and legume food crops as sole crops and intercrops. The chapter addresses the second objective of the study. The crops reported on include sorghum, cowpea and bottle gourd.

Chapter 7: is similar to Chapter 6 in that it also reports on field trials quantifying water use of sole crops and intercrops. The crops featured in the study included were maize landraces, bambara groundnut and dry beans.

Chapter 8: reports on AquaCrop model calibration and validation for the three sorghum genotypes used for the field trials (***cf.*** Chapter 4).

Chapter 9: reports on model calibration and validation for APSIM. The model was used to model the sorghum-cowpea intercrop (***cf.*** Chapter 6).

Chapter 10: reports on results of model application and extrapolation using AquaCrop to assess different agronomic management practices for sorghum sole crop. The chapter also provides a brief outline of possible best management practices for sorghum under rainfed conditions.

Chapter 11: reports on results of model application and extrapolation using APSIM to assess different agronomic management practices for sorghum-cowpea intercrop. The chapter also provides a brief outline of possible best management practices for sorghum under rainfed conditions.

Chapter 12: provides a holistic discussion of the entire project and links all the separate studies to achieving the project objectives. The chapter also provides the conclusion and recommendations for future studies.

References

Baye, T., Kebede, H., Belete, K., 2001. Agronomic evaluation of *Vernonia galamensis* germplasm collected from Eastern Ethiopia Industrial Crops and Products 14, 179–190.

Azam-Ali, S.N., 2010. Fitting underutilised crops within research-poor environments: Lessons and approaches. S. Afr. J. Plant & Soil 27, 293-298.

Collins, W.W., Hawtin, G.C., 1999. Conserving and using crop plant biodiversity in agroecosystems. *In* Collins, WW and Qualset, CO (Eds) Biodiversity in agroecosytems CRC Press, Boca Raton, Washington pp 267-281.

Department of Water Affairs and Forestry (DWAF). 2006. 1st Edn National water resource strategy: report Pretoria, South Africa.

Idowu, O.O., 2009. Contribution of neglected and underutilised crops to household food security and health among rural dwellers in Oyo State, Nigeria Proc IS on Underutilised Plants (Eds: Janicke *et al*) Acta Hort 806, 49-56.

Mabhaudhi, T., 2009. Responses of maize (*Zea mays* L) landraces to water stress compared with commercial hybrids MSc Thesis University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Mabhaudhi, T., 2012. Drought tolerance and water use of selected South African landraces of taro (*Colocasia esculenta* L. Schott) and Bambara groundnut (*Vigna subterranea* L. Verdc) PhD Thesis University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Mabhaudhi, T., Modi, A.T., 2013. Intercropping taro and bambara groundnut. In: Sustainable *Agriculture Reviews: Volume* 13, (Ed.) E. Lichtfouse. Springer International Publishing, Switzerland. DOI 10.1007/978-3-319-00915-5_9.

Modi, A.T., Mabhaudhi, T., 2013. Water use and drought tolerance of selected traditional crops. Water Research Commission Report (Report No. pending). WRC, Pretoria, South Africa.

Padulosi, S., 1998. Criteria for priority setting in initiatives dealing with underutilised crops. *In* Proceedings of the Europe European Symposium on Plant Resources for Food and Agriculture Braunschweig, Germany 29 June – 5 July. pp 55-96.

Republic of South Africa (RSA). 1998 National Water Act (Act 36 of 1998).

Schulze, R.E., 201.) Approaches towards practical adaptive management options for selected water-related sectors in South Africa in a context of climate change Water SA 37, 621-645.

Thrupp, L.A., 2000. Linking agricultural biodiversity and food security: the valuable role of biodiversity for sustainable agriculture International affairs 76, 265–281.

United Nations Population Fund (UNFP). 2011. State of the world population. People and possibilities in a world of 7 billion. www.unfpa.org/swp (accessed 07/06/2013).

Williams, J.T., Haq, N., 2002. Global research on underutilised crops. An assessment of current activities and proposal for enhanced cooperation. Southampton, UK: ICUC.

CHAPTER 2

DROUGHT TOLERANCE AND WATER USE OF CEREAL CROPS

Hadebe, S.T., Modi, A.T. and Mabhaudhi, T.

2.1 Introduction

Sub–Saharan Africa (SSA) has the highest percentage of food insecurity globally (Clover, 2003; FAO et al., 2014). Almost two out of every three people in SSA live in rural areas, relying principally on small–scale, rain–fed agriculture for their livelihood (FAO, 2014). In rural households, most food is produced and consumed locally (Garrity et al., 2010), making household agricultural productivity critical to improving food security (Schmidhuber and Tubiello, 2007). Rural poverty accounts for 83% of the total extreme poverty in SSA, and about 85% of the poor depend on agriculture for their livelihoods (Byerlee et al., 2005). Small–scale rainfed agriculture is the main livelihood source in arid and semi–arid areas of SSA. The yield levels in such farming systems are very low, especially during years of severe drought (Mavhura et al., 2015).

Sub–Saharan Africa comprises 43% of the area classified to an extent as arid (FAO, 2008). Under these conditions, water becomes the single most limiting factor to successful crop production. Climate change predictions for SSA suggest rainfall reduction, variable distribution pattern, increased erratic rainfall, intra–seasonal dry spells, and incidences of flooding, high temperatures, corresponding increased evaporative demand and higher frequency of droughts (Ringler et al., 2010; Schulze, 2011). This causes SSA crop production to be vulnerable because rainfed agriculture constitutes more than 95% of agricultural land use (Singh et al., 2011). This will effectively compound the existing challenges to crop production and food security hence underscoring the need for improving effective use of water in rainfed agriculture (Blum, 2009) as well as adoption of resilient crops (Alemayehu et al., 2012). In this context, resilient crops are those with a high ability to withstand or recover from water stress periods.

Cereal crops are a major source of dietary energy in the diets of people in SSA (Chauvin et al., 2012). In principle, producing cereal crops is water intensive. Past and current agricultural interventions have been focused on increasing production of high-energy crops to improve food availability and access. The approaches have also assumed that improved availability would lead to stability (less price volatility) and guarantee sustainable access. These efforts have mainly focused on a few energy rich cereal crops such as maize, wheat and rice. While this has led to huge improvements in terms of crop production, it has also resulted in some of the cereal crops being cultivated in less suitable areas while suitable cereal crops have been relegated (Mabhaudhi et al., 2016a). This success must be accompanied by matching cereal crops to suitable agro–ecologies and maximizing on their genetic potential (Sebastian, 2009); this could have greater impacts on food security. To ensure and improve food security, crop production, especially for staple food crops, should be focused on water conservation and improved water productivity.

Cereals are an important food source for human consumption and food security (FAO, 2014) and SSA cropping systems among rural subsistence farmers are largely cereal–based. The most widely cultivated cereal crops in SSA are maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), millet (*Pennisetum glaucum* L.), and rice (*Oryza sativa* L.) (Edmonds et al., 2009). Other cereals under production include wheat (*Triticum* spp.), barley (*Hordeum vulgare* L.), oats (*Avena sativa*), buckwheat (*Fagopyrum esculentum*) and teff (*Eragrostis tef* Zucc.) (Haque et al., 1986; World Bank, 2008). Of these, maize has high water requirements whilst wheat, barley and rice suffer high yield losses and crop failure under water stress and during drought periods. Millet and sorghum are indigenous crops to SSA renowned for their drought and heat tolerance. However, sorghum has a wider production distribution range, is produced on a larger area and has higher yield output than millet. Sorghum can tolerate temporal waterlogging which confers an advantage in flooding situations. Sorghum's drought, heat and waterlogging tolerance as well as adoption by farmers makes sorghum an ideal crop for production in SSA.

Despite sorghum being the second most grown cereal crop in SSA, the potential of sorghum's drought tolerance to contribute to improving water productivity is relatively still underutilised (Mabhaudhi et al., 2016b). This review proposes sorghum as an alternative cereal crop for cultivation in SSA to enhance water productivity and improve food security, especially in regions threatened by water scarcity. This article reviews water use of cereal crops produced in SSA and motivates for sorghum inclusion and/or promotion in arid areas of the region. This is done by reviewing cereal crop production in SSA, identifying agro–ecological zones (AEZs) and distribution thereof, identifying regions where inclusion and/or promotion of sorghum would benefit cereal production, and reviewing sorghum attributes, which make it uniquely poised as a niche crop in such regions.

2.2 Water Use of Cereals

2.2.1 Distribution of agro–ecological zones and comparative advantage of cereals

Land and water resources and the way they are used are central to the challenge of improving food security across the world. Agriculture in SSA is 95% rainfed (Singh et al., 2011) with very limited use of external inputs such as fertilizers. This means that the land's agricultural production of cereals depends almost solely on the agro–ecological potential (Sebastian, 2009). Agro–ecological zones are geographical areas exhibiting similar climatic conditions that determine their ability to support rainfed agriculture. Sub–Saharan Africa can be divided into six AEZs, differentiated by the length of the potential growing period for rainfed agriculture. Within these AEZs, rainfall ranges dramatically, from over 2 000 mm/year in central Africa to less than 400 mm/year in arid areas (Bationo et al. 2006; Ringler et al. 2010). These AEZs are deserts, arid, semi–arid, humid, sub–humid and highland regions. Sub–Saharan Africa comprises 17% arid area, 17% semi–arid and 9% dry sub–humid, totalling 43% of the continent classified to an extent as arid (FAO, 2008). About 60% of SSA is vulnerable to drought, with 30% of it considered as highly vulnerable (Mavhura et al., 2015).

Production of cereal crops in suitable AEZs with a comparative advantage can potentially increase water productivity under rainfed cropping systems. This could increase crop yields without a corresponding increase in water use. Agriculture has seen a shift from increasing production through increasing area under cultivation to focusing on water conservation and increasing water productivity (Machethe et al., 2004; Fanadzo et al., 2010). Despite this, cereal production systems and trends in SSA remain largely unchanged and dominated by maize production, even in arid regions. Cereal crop production increases have been due to improvements in breeding and increased production area rather than improved water productivity.

2.2.2 Cereal crop production in SSA

Sub–Saharan Africa's rural economy remains strongly agro–based relative to other regions (Livingston et al., 2011). As such, economic growth focused on agriculture has a disproportionately positive impact in reducing food insecurity. In SSA, cereals are a staple food for, and mostly produced by, resource–poor farmers. Cereals and cereal products are an important source of energy, carbohydrate, protein and fibre, as well as containing a range of micronutrients such as vitamin E, some of the B vitamins, magnesium and zinc (McKevith, 2004). Land under cereal production in SSA in 2008 was 92 132 298 hectares (World Bank, 2008). The most widely cultivated cereal crops in SSA are maize, sorghum, millet and rice, respectively (Edmonds et al., 2009). Being the largest crop produced, maize has cultural, economic, and political significance in SSA and is the dominant staple food for much of eastern and southern Africa while greater dependence on millet, rice, and sorghum is found in western Africa (Doward et al., 2004).

Among the staple cereal crops, rice and maize have high water requirements (Table 2.1); hence, production of cereal crops with low water requirements provides a comparative advantage in water scarce areas (Table 2.2). In large parts of SSA, maize is the principal staple crop, covering approximately 27 Mha. Maize accounts for 30% of the total area under cereal production in this region: 19% in West Africa, 61% in Central Africa, 29% in Eastern Africa and 65% in Southern Africa (FAO, 2010; Cairns et al., 2013). In southern Africa, maize is particularly important, accounting for over 30% of the total calories and protein consumed (FAO, 2010). Among SSA AEZs, the sub–humid zone constitutes 38% of the total land area in SSA and has favourable rainfall (700–200 mm per annum) for maize production (Zingore, 2011). Maize yields have stagnated and in some areas declined in SSA. One of the primary reasons is lack of use of drought ameliorative measures (Fischer et al., 2014). This AEZ land area and rainfall is sufficient for production of maize and other high water requirement cereals lacking drought and heat tolerance. Rice lies fourth in area SSA area under production. In the decade, the growth of rice yield has dropped below 1% per year worldwide and low yield constitutes one of the main challenges of rice production in SSA. Rice production is increasingly constrained by water limitation and increasing pressure to reduce water use in irrigated production because of global water crisis (Zhang et al., 2012). Breeding attempts have resulted in Rice for Africa (NERICA) initiative, which has led to the release of upland NERICA varieties with relatively less water use compared to traditional lowland rice (Akinbile et al., 2007). However, even the NERICA varieties still have significantly higher water requirement and are still subject to extensive testing and drought evaluation (Matsumoto et al., 2014). Heat and drought stress usually occur concurrently (Rizhsky et al., 2002), hence lack of heat stress in NERICA rice remains a concern for production in arid and semi–arid SSA.

Table 2.1: Growing conditions, production statistics and water use characteristics of major cereals in SSA.

Cereal type	[1]Water use (mm) per growing season	[1]Average growing period (days)	Stress tolerances	Water productivity *(WP) (kg m^{-3})	Water use efficiency *(WUE) (kg ha^{-1} mm^{-1})
Maize	500–800	125–180	–	[5]1.1–2.7	[14]7.6–10.4
Sorghum	[3,6]450–650	115–130	Heat, drought, temporal waterlogging and salinity	[8]0.6–2.7	[4]12.4–13.4
Wheat	450–650	120–150	–	[5,16]0.6–2.0	[2]9.7–11.0
Rice (paddy)	[11]450–940	90–150	Waterlogging and flooding	[5]0.6–1.6	[11]4.5–10.9
Barley	450–650	120–150	–	[7]0.7–1.5	[15]7.7–9.7
Millet	450–650	105–140	Heat and drought	[12]0.4–1.0	[4,10]5.1–10.4
Teff	450–550	150–165	Drought and waterlogging	[9]0.6–1.2	[13]4.2–11.2

*WP and WUE values were quoted for grain yields where water use was above minimum crop water requirements. However, rainfall distribution was disregarded (Sources: [1]FAO, 1991; [2]Zhang et al., 1998; [3]Hensley et al., 2000; [4]Maman et al., 2003; [5]Zwart and Bastiaanssen, 2004; [6]Jewitt et al., 2009; [7]Araya et al., 2011b; [8]Mativavarira et al., 2011; [9]Abdul-Ganiyu et al., 2012; [10]Ismail, 2012; [11]Zhang et al., 2012; [12]Mokh et al., 2013; [13]Yihun et al., 2013; [14]Ofori et al., 2014; [15]Barati et al., 2015; [16]Virupakshagowda et al., 2015).

Table 2.2: Agro–ecological zones, their distribution in SSA and cereal crops with comparative advantage in each region.

[1]Agro–ecological zone	[1]Length of growing period (days)	[1]Average annual rainfall (mm)	[1,3]Land area (% of SSA)	*[1]Main soil types	[1,2]Main cereal crops produced	Cereal crops with comparative advantage
Arid	< 90	0–600	17	Lithosols, xerosols	Maize, sorghum, millet	Sorghum, millet
Semi-arid	90–179	600–1400	17	Lixisols, arenosols, vertisols	Maize, sorghum, millet	Sorghum, millet
Sub-humid	180–269	1400–3000	[3]38	Ferralsols, lixisols, acrisols	Maize, sorghum, millet	Maize, wheat, barley
Humid	> 270	3000–4500	20	Ferralsols, acrisols	Maize and rice	Maize, rice
Highlands	180–270	1400–4500	3	Vertisols, cambisols	Wheat and barley	Rice

*soil forms have been simplified for purposes of this review. (Sources: [1]Livingston et al., 2011; [2]FAOSTAT, 2013; [3]Zingore, 2013).

Wheat and barley have lower water requirements in comparison to maize and rice, which makes them suitable for cultivation in low rainfall areas. However, these crops are still susceptible to drought and heat stress and suffer high yield losses under water stress. Teff, millet and sorghum have low water requirements befitting rainfall ranges in arid and semi–arid regions. Additionally, these three crops exhibit drought and heat stress tolerance. Sorghum and millet are highly drought tolerant whilst teff exhibits a moderately sensitive and linear response to water stress (Araya et al., 2011a). Sorghum, among the three cereals, is particularly suited for arid and semi–arid AEZs in SSA as it is uniquely tolerant to temporal waterlogging. Temporal waterlogging tolerance is important under conditions of extreme, erratic rainfall, which is experienced by crops in SSA.

It has previously been suggested that increasing productivity of cereals will improve food security in the region (Romney et al., 2003). However, it is not about 'any' but rather about improving the production of cereal crops that are suited to SSA's AEZs. The major crops in terms of production area, consumption trends and research attention are currently overshadowing cereal crops that have desirable water use characteristics. This 'business–as–usual' approach to cereal production has resulted in declining yields for major crops such as maize (Fischer et al., 2014) and general neglect of alternative cereal crops with potential to contribute to food security in marginal AEZs. Since water is the predominant limiting factor in crop production within SSA, a starting step would be reviewing the water use of the different cereal crops. This would allow fitting them into specific AEZs where each cereal crop possesses a comparative advantage.

2.2.3 Water use characteristics of cereal production in SSA

To improve cereal yield in arid and semi–arid AEZs, it is important to understand their crop water use. Under rainfed agriculture, water use efficiency (WUE) of major cereal crops becomes a key factor in increasing yield under water scarcity (Blum, 2005). Water use efficiency is the yield output per unit evapotranspiration (soil evaporation plus crop transpiration) (Mabhaudhi et al., 2016a). To obtain WUE in cereal grain crops, the mass of the yield portion (pinnacle, cob, head etc.) is divided by crop water use (evapotranspiration) from sowing to physiological maturity. This should not be confused with water productivity (WP), which is the yield output per unit of water transpired by the crop (Steduto et al., 2007). The difference between WUE and WP is highlighted below in the equations used to calculate them.

$$WUE = \text{Total biomass or yield} / \Sigma \text{ Evapotranspiration} \qquad \text{Equation 2.1}$$

$$WP = \text{Total biomass or yield} / \Sigma \text{ Transpiration} \qquad \text{Equation 2.2}$$

Water use efficiency is a function of several factors, including crop physiological and morphological characteristics, genotype, planting population, soil characteristics such as soil water holding capacity, meteorological conditions and agronomic practices. In order to optimize yield under water limiting conditions, an ideal cereal crop should have a long and dense root structure, stay–green characteristics, and high harvest index and maintain high WUE under stress. To improve WUE, integrative measures should aim to optimize cultivar selection and agronomic practices (Azizian and Sepaskhah, 2014).

Among the agronomic practices for improving WUE is crop selection. Multiple approaches have been proposed to improve cereal production in arid and semi–arid environments of SSA e.g. supplementary irrigation and breeding for drought tolerance in major crops (Ortiz et al., 2007; Edmeades et al., 2009; Kijne et al., 2009; Cairns et al., 2013). In this review, we propose production, promotion and inclusion of suitable drought tolerant cereal crops to improve water use efficiency under arid and semi–arid AEZs of SSA. In comparison to teff and millet, sorghum has higher WUE (Table 2.1). Additionally, sorghum has the highest tonnage and number of SSA countries producing it. Lowest annual rainfall is experienced in arid and semi–arid AEZs of SSA. The situation is exacerbated by that received annual rainfall generally is not available throughout a crop's growing season (Table 2.2). Therefore, actual rainfall received during a growing season is often lower than quoted figures and highly irregular. This makes sorghum production in arid and semi–arid regions of SSA a viable alternative (Table 2.2) for increasing water productivity in the region.

Maize and sorghum have the highest upper water productivity thresholds compared to other cereals discussed in this review (Table 2.1). This implies that both crops have the highest water use potential, and are preferred for production under conditions of zero or minimal soil evaporation. This can be attributed to relatively high yields in maize compared to sorghum, and relatively low crop water requirements in sorghum compared to maize. This means that maize can attain higher yields using more water than sorghum, whilst sorghum attains lower yields using less water than maize. High yield potential thus gives maize comparative advantage for production in sub–humid and humid regions of SSA (Table 2. 2). However, sorghum has higher water use efficiency than maize mainly due to high tolerance to abiotic and biotic stresses (Table 2.1). Thus, cropping sorghum is advantageous for production under water limited areas arid and semi–arid regions of SSA.

Climate variability and change impacts in SSA will mainly be felt through water i.e. increased frequency of rainfall extremes such as droughts and floods (Schulze, 2011). Increasing rainfall variability will also expose crops to episodes of intermittent water stress (Chivenge et al., 2015). In addition, the percentage semi– and arid area of SSA is predicted to increase thus suggesting an increase in marginal agricultural production areas. Therefore, we can no longer afford to sideline the production of drought and heat stress tolerant cereals.

2.2.4 Impacts of climate change on cereal crop production

Cereal crop production in SSA is projected (based on IFPRI IMPACT modelling) to decline by a net 3.2% by 2050 because of climate change. This will largely be due to projected increased incidence of drought and temperatures warming above global average. The largest negative yield impacts are projected for wheat (–22%), maize (–5%) and rice (–2%), respectively. Increasing the area under cereal crop production by 2.1% will partially compensate for overall yield growth decline. On the contrary, millet and sorghum yields are projected to increase slightly under climate change given their drought and heat stress tolerance (Ringler et al., 2010). This highlights that the major cereals' (maize, rice and wheat) capacity to meet the food requirements of a growing population will be negatively impacted. As such, current research efforts for major cereal crops is targeted at breeding drought and heat stress tolerant cultivars that will be able to produce under these conditions.

On a positive note, these simulations suggest that under conditions of increasing water scarcity and high temperature, millet, sorghum and other drought and heat tolerant crops may become future cereal crops for production in SSA. However, current trends show that, in terms of land area under cereal production, sorghum and millet still lag behind maize even in arid regions of SSA. This implies that potential of sorghum is currently underutilised in the region. There is a need to promote sorghum as a possible future crop. In order to do this, there is need for empirical data describing its morphological, phenological and physiological characteristics that make it suited for production in water scarce regions. This knowledge will be important in exploiting the potential of sorghum in arid and semi–arid regions of SSA.

2.3 Sorghum Adaptation to Water Stress

The effect of drought stress depends on the plant developmental stage at the onset of stress. Under field conditions, drought stress can occur at any stage of crop growth ranging from seedling establishment, vegetative, panicle development and post–flowering, and the period between grain filling and physiological maturity (Rosenow and Clark, 1995; Rosenow et al., 1996). Sorghum is reputed for its ability to tolerate water stress, both intermittent and terminal stress. This is mostly attributed to its dense and prolific root system, ability to maintain relatively high levels of stomatal conductance, maintenance of internal tissue water potential through osmotic adjustment and phenological plasticity (Tsuji et al., 2003). Water stress responses in sorghum can be of physiological, morphological and phenological in nature. Sorghum genotypes differ in their degree of drought tolerance, especially with respect to the timing of stress. Sorghum genotypes that exhibit good tolerance during one developmental stage may be susceptible to drought during other growth stages (Akram et al., 2011). Such genotypic variation with respect to responses to water stress allow for farmers to select varieties which best suit local farming conditions and hence making sorghum suitable to a range of conditions.

2.3.1 Physiological adaptation

Ability to maintain key physiological processes, such as photosynthesis, during drought stress is indicative of the potential to sustain productivity under water deficit. Sorghum exhibits physiological responses that allow continued growth under water stress (Dugas et al., 2011). Delayed senescence, high chlorophyll content and chlorophyll fluorescence as well as low canopy temperature and high transpiration efficiency are physiological traits that confer drought tolerance to sorghum (Harris et al., 2006; Kapanigowda et al., 2013). From a crop improvement perspective, manipulating these traits can increase drought tolerance in sorghum.

Crop species reduce photosynthesis through modification of photosynthetic apparatus under water stress. Reduction in chlorophyll content forms part of that modification (Kapanigowda et al., 2013) to water stress. Chlorophyll content is genotype dependent, and varies according to plant stage (Van Oosterom et al., 2010; Wang et al., 2014). Delayed senescence or 'stay green' is the ability of the plant to retain greenness during grain filling under water-limited conditions (Borrell et al., 2014). Delayed leaf senescence in sorghum allows continued photosynthesis under drought conditions, which can result in normal grain fill and larger yields compared with senescent cultivars (Tolk et al., 2013).

Stomatal conductance mediates the exchanges of water vapour and carbon dioxide between leaves and the atmosphere. Sensitivity of sorghum stomatal conductance to soil water availability and vapour pressure deficit varies between genotypes. Sorghum partially closes stomata, rolls leaves and has a narrow leaf angle in response to water and heat stress, effectively reducing transpiration and exposure area to solar radiation. Under intermittent water stress, partial closure of stomata is used to sustain reduced photosynthetic activity, which ultimately results in high and stable WUE in sorghum compared to other drought susceptible cereals (Takele and Farrant, 2013).

Osmotic adjustment is conservation of cellular water content. In sorghum, osmotic adjustment is associated with sustained biomass yield under water–limited conditions across different cultivars (Blum, 2005). Osmotic adjustment helps maintain higher leaf relative water content at low leaf water potential under water stress; this sustains growth while the plant is meeting transpirational demand by reducing its leaf water potential (Blum, 2005). The osmotic potential is adjusted through changes in the accumulation of proline, inorganic ions, and other osmotic solutes (Sonobe et al., 2011). Increased deep soil water capture has also been found to be a major contribution of osmotic adjustment in sorghum (Blum, 2005). Typically, in sorghum older leaves are selectively senesced under stress, while the remaining young leaves retain turgor, stomatal conductance, and assimilation because of high osmotic adjustment in the younger leaves (Blum and Arkin, 1984). This ensures photosynthetic activity by keeping top leaves green, and reduced transpiration water losses by older shaded leaves under water stress. In addition, sorghum has an effective transpiration ratio of 1:310, as the plant uses only 310 parts of water to produce one part of dry matter, compared to a ratio of 1:400 for maize (Du Plesis, 2008). Hence, production of sorghum in water scarce regions as an alternative to maize will conserve water and increase water productivity.

2.3.2 Morphological adaptation

Drought tolerance in sorghum is consistent with its evolution in Africa where domestication occurred in arid and semi–arid areas parts of northern Africa (Morris et al., 2013). This resulted in the development of heritable morphological and anatomical characteristics (Duvas et al., 2011). These attributes minimize yield losses associated with water stress.

The root system is the plant organ in charge of capturing water and nutrients, besides anchoring the plant into the ground. It is naturally viewed as a critical organ to improve crop adaptation to water stress (Vadez, 2014). Under water limiting conditions, water extraction by a dryland crop is limited by root system depth and by the rate of degree of extraction (Robertson et al., 1993). Sorghum has long roots with high root density at deeper depths (Schittenhelm and Schroetter, 2014) with roots that can reach up to 2 m (Robertson et al., 1993) in the absence of impeding soil layers. This allows sorghum to access water lower down the soil profile during water scarce periods. Water stress can be detrimental at vegetative stage if it inhibits root growth (Niakan et al., 2013). However, this is seldom the case as under water stress dry matter partitioning will often favour root growth at the expense of vegetative growth (Mabhaudhi, 2009). Maximum rooting depth usually occurs after anthesis (Robertson et al., 1993). Drought tolerance and water extraction efficiency in sorghum are associated with maintaining high root length density, number of nodal roots and late metaxylem vessels per nodal root under water scarcity (Tsuji et al., 2005). For optimal root development, it is important that pre–flowering water stress be avoided.

Long, narrow, pointy leaves reduce the contact surface area with direct sunlight during high temperatures hence preventing desiccation. Sorghum leaves and stem are covered by a waxy cuticle and epicuticular wax (Saneoka and Ogata, 1987) preventing excessive water loss during water stress. This suggests that cuticle and epicuticular wax enhances WUE in sorghum during water stress.

Tillering ability is commonly associated with sorghum in regions with limited rainfall. Tillering is generally recognized as one of the most plastic traits affecting biomass accumulation and ultimately grain yield in many field crops (Kim et al., 2010). Genetic variation in tillering affects the dynamics of canopy development and hence the timing and nature of crop water limitation (Hammer et al., 2006). Simulation studies on sorghum (Hammer et al., 1996) indicated significant yield advantage of high–tillering types in high–yielding seasons when water was plentiful, whereas such types incurred a significant disadvantage in lower yielding water–limited circumstances. However, tillering has been bred out of commercial cereal cultivars to ensure maximum biomass partitioning to the yield portion. Nonetheless, tillering is a prominent feature in sorghum landraces cultivated by subsistence farmers (Pandravada et al., 2013) as these have not been the subject of deliberate crop improvement. Whether tillering in landraces is beneficial in arid and semi–arid SSA remains unclear; however, the fact that landraces still tiller may suggest that subsistence farmers find an advantage to this trait. It may be that such farmers associate tillering with yield compensation under stressful conditions. Studies done by Lafarge et al. (2002) could not associate tillering with either yield or drought tolerance. However, it is likely that emergence of tillers is genetically controlled and partly serves as a survival mechanism under water stress conditions. Hence, the selection of the best genotype is confounded by genotype–by–environment interactions for tillering (Hammer et al., 2005).

2.3.3 Phenological adaptation

Sorghum utilises quiescence adaptive mechanisms to allow for extreme drought tolerance (Dugas et al., 2011). It can remain visually dormant during drought conditions, resuming growth once conditions are favourable (Assefa et al., 2010) ensuring crop survival and yield under terminal stress. Water stress affects sorghum at both pre– and post–flowering stages of development. Pre–flowering drought stress response occurs when plants are under significant water stress prior to flowering, particularly at or close to panicle differentiation and until flowering (Kebede et al., 2001). The most adverse effect of water stress on yield occurs during and after anthesis (Blum, 2004). Post–flowering drought stress significantly reduces the number and size of the seeds per plant (Rosenow and Clark, 1995) which are the main causes for lower grain yield in sorghum

(Assefa et al., 2010). Phenological plasticity of sorghum allows for shorter or delayed seasons in sorghum to minimize effect of water stress on yield.

2.3.4 Water use efficiency

Water use efficiency captures the yield response of physiological, morphological and phenological adaptations to water stress. When water is scarce, understanding the magnitude of water consumption is important. In most cases, evaluation for decision-making requires information about efficiency – when water is being used, is it being used effectively. Water use efficiency in sorghum is variety specific. During water stress, reduction in sorghum biomass production is minimised while water use is significantly lowered. Hence, maximal water use efficiency (WUE) is attained under water scarcity conditions, while lowest WUE values are obtained when environmental conditions are optimal for crop growth (Abdel–Montagally, 2010).

Sorghum daily water–requirements vary according to crop growth stage (Boyer, 1982; Abdel–Montagally, 2010), with maximal water requirement occurring from booting until after anthesis. Consequently, at this stage sorghum is most sensitive to water stress. During the grain filling stage, physiological maturity and senescence, water–requirements decrease gradually. Maximum sorghum yield requires 450 to 650 mm of water distributed evenly over the growing season (Doorenbos and Hassam, 1979; Assefa et al., 2010). Sorghum grain yields are comparable to maize, and higher than those of other major cereals under optimal water availability (Table 2.1). Under water stress, sorghum produces more yield than other major cereals due to a superior WUE (Table 2.1). This reaffirms the fact that sorghum is a drought tolerant crop capable of producing reasonable yields under water stress. Therefore, sorghum is uniquely poised as a niche crop in semi–arid and arid regions of SSA.

2.4 Sorghum Nutritional Value and Utilization

2.4.1 Nutritional responses to water stress

Cereal grains are an optimal source of energy, carbohydrates, protein, fibre, and macronutrients, especially magnesium and zinc (Kowieska et al., 2011). Water stress negatively affects grain nutritional content in cereals. A reduction in nutritional value of grains is most pronounced when water stress occurs during grain filling (Zhao et al., 2009). Knowledge of the extent to which water stress affects grain nutritional content in sorghum is lacking. Nutritional water productivity (NWP) is an emerging concept that combines information of nutritional value with that of crop water productivity. The result is an index that includes nutritional value–based output per unit of water use. This concept is important in addressing food security issues, especially in arid and semi–arid regions where malnutrition remains high. The review of literature showed that no NWP values have been developed for major cereals, including sorghum. This complicates assessment of which cereals crops have nutritional advantage in water scarce regions of SSA. Since sorghum exhibits superior drought tolerance to major cereals, it is expected that reduction in nutrient content be minimised under water stress. However, studies need to be conducted to ascertain the effect of water stress on the nutritional value of sorghum.

2.4.2 Utilization, nutrition and health

Sorghum is used in a variety of food products across SSA. Food type and preparation varies by country and cultural practices. Sorghum is part of diets of many people in SSA and is consumed as traditional foods or commercial products (Taylor, 2003). These include: *bouillie* (thin porridge), *tô* (stiff porridge prepared by cooking slurry of sorghum flour), *couscous* (steamed and granulated traditional food), *injera* (fermented pancake–like bread prepared from sorghum in Ethiopia), *nasha* and *ogi* (traditional fermented sorghum foods used as weaning food), *kisra* (traditional bread prepared from fermented dough of sorghum), baked products and traditional beers (*dolo, tchapallo, pito, burukutu,* (Mahgoub et al., 1999; Yetneberk et al., 2004; Achi, 2005; Dicko et al., 2005). Pre–cooked sorghum flour mixed with vitamins and exogenous sources of proteins are commercially available in many African countries for the preparation of instant soft porridge for infants. Sorghum can also be puffed, popped, shredded and flaked to produce ready–to–eat breakfast cereals (Dicko et al*.,* 2006).

Sorghum nutritional composition is comparable to other major cereals (Hulse et al., 1980; FAO, 1995; Ragaee et al., 2006), which makes promotion and inclusion of sorghum in water scarce regions of SSA a good alternative from a nutrition standpoint. The average energy value of whole sorghum grain flour is 356 kcal per 100 g, which is comparable to other cereals (Fig 2.1). Starch is the main component of sorghum grain, followed by proteins, non–starch polysaccharides and fat. The protein content in whole sorghum grain is in the range of 7–15% (Dicko et al*.,* 2006). The fat content, present mainly in the germ of the sorghum grain, is rich in polyunsaturated fatty acids, with a similar composition to maize fat. Sorghum is a good source of vitamins, mainly the B vitamins and the liposoluble vitamins A, D, E and K, and is a good source of more than 20 minerals including phosphorus, potassium, iron and zinc (Anglani, 1998; Glew et al., 1997). Sorghum is important for human health in other respects. It is rich in fibre, bioactive compounds and antioxidant rich phytochemicals that are desirable in human health (Awika and Rooney, 2004; Dicko et al., 2005; Dykes et al., 2005; Rooney, 2007). Decreasing human consumption of sorghum in SSA (Sheorain et al., 2000; Adegbola et al., 2013) indicates that sorghum maybe underutilised in SSA despite comparable nutritional composition to major cereals.

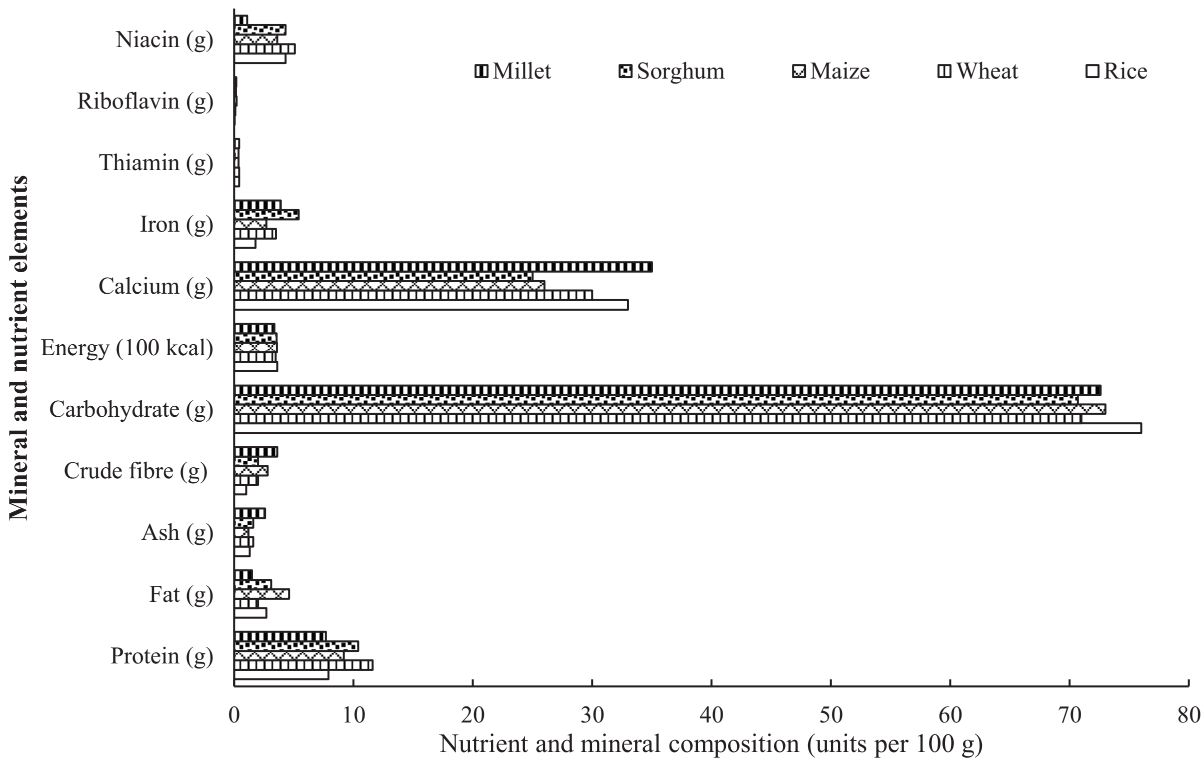

Figure 2.1: Grain nutrient composition (per 100 g at 12 percent moisture) of five major cereals produced in sub–Saharan Africa. (Sources: FAO, 1995; Dicko et al., 2006).

2.5 Sorghum Underutilization in SSA

Is sorghum an underutilised crop of SSA? This question calls into debate the issue of what are underutilised crops? The critical issue here is the lack of a consensus definition describing neglected and underutilised crop species (NUS) (Mabhaudhi et al., 2016b). Several studies have described the typical features of NUS and the overriding issues affecting the conservation and use of their genetic resources (Padulosi et al., 1999; Williams and Haq, 2002; Padulosi et al., 2008;

Galluzi and Lopez Noriega, 2014). Neglected and underutilised crop species are generally referred to as those species whose potential to improve people's livelihoods, as well as food security and sovereignty, is not being fully realized because of their limited competitiveness with commodity crops in mainstream agriculture (Padulosi et al., 2011). There is also the question of underutilised by who, where and to what extent (Padulosi, 1999). Elsewhere, the term underutilised has been associated with a crop being under–researched (Mabhaudhi et al., 2016a). Mabhaudhi et al. (2016b) described underutilised crops "as a subset of biodiversity that has been primarily maintained by resource poor farmers in low input, mixed systems, and which is declining in significance due to a range of factors."

Regarding typical features of NUS and the overriding issues affecting the conservation and use of their genetic resources, sorghum in SSA can be excluded from classification as underutilised. The existence of International Crops Research Institute for the Semi–Arid Tropics (ICRISAT), large collections of germplasm collections and large-scale production throughout the region disqualify sorghum on basis of such features. An estimate of 168,500 accessions (most of which are duplicates of the ICRISAT 36 774 world collection accessions) is contained in sorghum germplasm collections globally at multiple sorghum genetic resources conservation sites (Rosenow and Dahlberg, 2000).

Landraces constitute 85.3%, breeding material 13.2%, wild species accessions 1.2% and named cultivars 0.3% of the total collection. The high percentage of landraces in comparison to improved varieties in the total collection suggests that sorghum genetic resources are underutilised in respect to crop improvement. Landraces and obsolete cultivars can be considered as a valuable portion of the gene pool because they represent the broad intra–specific genetic diversity of crops, therefore provides valuable characteristics important for breeding (Hermuth et al., 2010). However, this presents a breeding advantage over major cereals like maize, wheat and barley where the breeding material is below 10%.

Advanced features used in determining whether a crop is underutilised are geographical distribution and socio–economic status. With regard to geographical distribution, a species could be underutilised in some regions but not in others. Regarding the socio–economic implication of the term, many species represent an important component of the daily diet of millions of peoples but their poor marketing conditions make them largely underutilised in economic terms. As such, a crop can be widely cultivated across a region and still be underutilised. Geographically, maize remains the main crop under production (Table 2.3 and Fig 2.2) even in semi–arid and arid parts of SSA where sorghum production confers a comparative advantage. Socio–economically, human consumption of sorghum is decreasing with enhanced socio–economic status of population and easy availability of much preferred cereals in abundance and at affordable prices (Sheorain et al., 2000; Adegbola et al., 2013; Orr et al., 2016). The grain stands to contribute more to food security than at present, especially for in arid and semi–arid SSA (Adegbola et al., 2013) if promoted and included more in the cereal food value chain. Relative to its potential, sorghum in SSA is therefore underutilised in terms of "extent" (socio–economic) and "where" (geographical).

Table 2.3: Cereal production statistics in countries with arid and semi-arid AEZs in SSA.

Country	[1,2]Country area (1000 ha)	[1]Agricultural area	[1]Cereal production area	Ranking of 5 main cereals and area under production (1000 ha)[1]									
				1		2		3		4		5	
				Crop	Area	Crop	Area	Crop	Area	Crop	Area	Crop	Area
Botswana	58 173	25 920	146	A	870	B	500	C	580	–	–	–	–
B. Faso	27 422	11 770	4 210	B	1 807	C	1 327	A	9 136	D	139	–	–
Chad	128 400	49 932	2 542	B	850	C	800	A	300	C	205	E	17
Cameroon	47 544	9 750	–	A	832	B	800	D	167	C	70	E	1
Eritrea	11 760	7 592	440	B	250	C	55	F	45	E	25	A	20
Ethiopia	110 430	36 325	10 243	A	2 069	B	1 847	E	1 706	F	1 048	C	432
Kenya	58 037	27 430	2 494	A	2 028	B	189	E	313	C	88	D	30
Malawi	11 848	5 585	1 881	A	1 677	B	89	D	65	C	49	E	1
Mali	124 019	41 651	3 661	C	1 437	B	938	A	641	D	605	E	7
Namibia	82 429	38 809	276	C	230	A	28	B	16	E	2	–	–
Niger	126 700	44 482	10 242	C	7 100	B	3 100	A	15	D	13	E	2
Nigeria	92 377	71 000	17 545	B	5 500	A	5 200	C	4 000	D	2 600	E	80
Senegal	19 671	9 015	1 117	C	714	A	152	B	140	D	108	–	–
Somalia	63 766	44 129	398	B	270	A	124	E	3	D	1	–	–
S. Africa	121 909	96 374	3 993	A	3 250	E	520	F	80	B	60	G	27
Sudan	112 702	108 678	10 088	B	7 136	C	2 782	E	136	A	27	D	8
Tanzania	93 300	–	–	A	–	D	–	B	–	C	–	E	–
Zambia	75 261	23 636	1 145	A	998	E	42	D	39	C	34	B	23
Zimbabwe	39 076	16 400	1 379	A	900	C	230	B	230	E	10	F	< 1
Total				**A**	**4 907**	**B**	**4 125**	**C**	**2 687**	**D**	**1 175**	**E**	**1 159**

(Sources: [1]FAOSTAT, 2013; [2]WDI, 2015). Note: Ranking of five main cereals and area under production in Eritrea and Ethiopia according FAOSTAT (2013) excludes teff, which is the main grain cereal under production (Yihun et al., 2013). Where: A is maize; B is sorghum; C is millet; D is rice; E is wheat; F is barley; and G is oats.

2.6 Challenges and Outlook to Increasing Sorghum Production and Utilization in SSA

Multiple challenges account for sorghum underutilization in SSA. The major challenges identified in literature being:

- Sorghum cultivation is characterized by low inputs traditional farming practices, using traditional cultivars or landraces, which results in low yields (Taylor, 2003; Hellums and Roy, 2014).
- Lack of surplus sorghum, without which processing industries fail to establish which hampers the promotion of sorghum–based food products (Taylor, 2003).

False perception of sorghum and historical stereotype of sorghum as a 'poor man's crop' which shifts consumer food preference to maize, wheat and rice based foods (Williams et al., 2012; Orr et al., 2016).

- Low availability of high–end processed sorghum foods in comparison to other major cereals (Oot et al., 1996).
- Bird destruction remains a key sorghum yield reduction threat in the region, forcing smallholder farmers to trade–off high yield potential and palatability for bird proof characteristics (Habindavyi, 2009)
- Low research attention, breeding efforts and adoption rates of improved varieties by farmers in favour of other major cereal crops (Mwadalu and Mwangi, 2013).

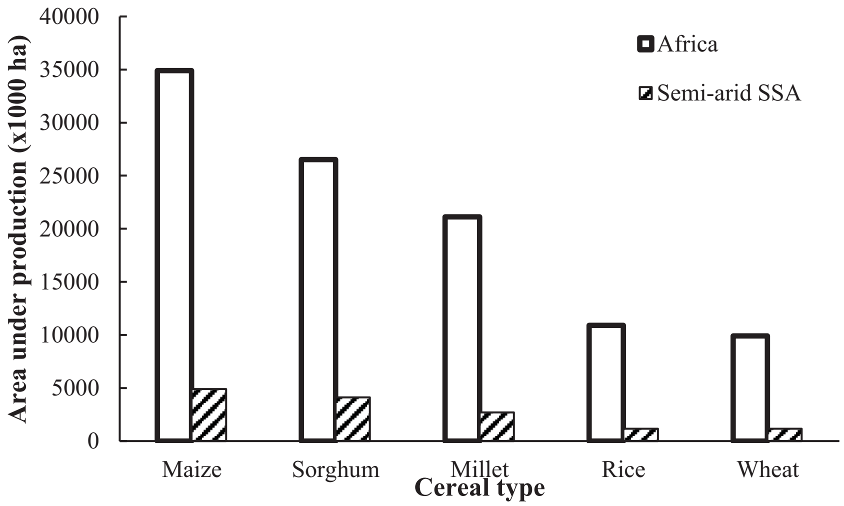

Figure 2.2: Cereal production statistics in terms of area under production in Africa and in 19 selected countries (see Table 2. 3) with arid and semi–arid agro–ecological zones in sub–Saharan Africa.

In this review, we suggest the following strategies to mitigate food insecurity through sorghum production in SSA.

- Green revolution (application of fertilizer, cultivation of improved cultivars and varieties) has potential to increase yields thereby providing surplus produce to drive the agro–processing industry of sorghum.
- Research into discriminatory mechanisms to remove tannins from seeds at the post–harvest stage could assist resolve the 'unhealthy dilemma' of choosing between bird proof traits and palatability.
- Use of participatory fashioned approaches towards development and distribution of new cultivars to improve cultivar adoption and sorghum breeding in the region.
- A drive towards marketing and distribution of existing sorghum high-end products, accompanied by investment and development of new processed products that compete well with that of other major cereals.

2.7 Conclusion

Sorghum is socio-economically and geographically underutilised in SSA. Sorghum production still lags behind maize even in arid and semi-arid AEZs where sorghum confers a comparative advantage. High WUE, adaptation to water stress, high germplasm variability, comparative nutritional value, and existing food value chain makes sorghum uniquely suited to improving cereal water productivity under water scarcity. How sorghum grain nutrients compare to that of other major cereals under water stress is unclear due to lack of NWP values for grain cereals. Rain-fed cultivation of sorghum as an alternative to major cereals in arid, semi-arid and drought prone AEZs of SSA, and promotion of sorghum traditional and commercial food products can potentially improve food security in the region. The main challenges affecting sorghum underutilization in SSA include low availability of surplus produce for production of high-end product processing, relatively low research attention afforded to sorghum and number of improved genotypes, low adoption rate of improved varieties, significant yield reduction due to bird damage, and consumer dietary preferences driven by perceptions of sorghum as a poor man's crop. Use of green revolution principles by smallholder farmers, participatory fashioned research approaches, development of tannin discriminating post-harvest processing technologies, and improved marketing and distribution of sorghum products can potentially improve sorghum production in SSA agriculture.

References

Abdel-Montagally, F.M.F., 2010. Evaluation of water use efficiency under different water regimes in sorghum (*Sorghum bicolor* (L.) Moench). World J. Agric. Sci. 6, 499– 505.

Abdul-Ganiyu, S., Amaanatu, M. K., Korese, J. K., 2012. Water use efficiency and productivity for rice (*Oryza sativa*) in the Bontanga irrigation scheme of northern region of Ghana. Agric. Sci. Res. J. 2, 362–368.

Achi, O.K., 2005. The potential for upgrading traditional fermented foods through biotechnology. Afr. J. Biotechnol. 4, 375–380.

Adegbola, A. J., E. F. Awagu, R. Q. Kashetu, 2013: Sorghum: the most under-utilized grain of the semi-arid Africa. Adv. J. Agric. Res. 1, 11–19.

Akinbile, C.O., Sangondoyin, A.Y., Nwilene, F.E., Futakuchi, K., 2007. Growth and yield responses of upland rice (NERICA2) under different water regimes in Ibadan, Nigeria. Res. J. Agron. 1, 71–75.

Akram, Z., Khan, M. M., Shabbir, G., Nasir, F., 2011. Assessment of genetic variability in sorghum genotypes for drought tolerance based on RAPD analysis. J. Agric. Res. 49, 455–463.

Anglani, C., 1998. Sorghum for human food: a review. Plant Foods Human Nutr. 52, 85–89.

Araya, A., Stroosnijder, L., Girmay, G., Keestra, S.D., 2011a. Crop coefficient, yield response to water stress and water productivity of teff (*Eragrostis tef* (Zucc.)). Agric. Water Manage. 98, 775–783.

Araya, A., Solomon, H., Mitiku, H., Sisay, F., Tadesse, D., 2011b. Determination of local barley (*Hordeum vulgare*) crop coefficient and comparative assessment of water productivity for crops grown under the present pond water in Tigray, northern Ethiopia. Momona Ethiopian J. Sci. 3, 65–79.

Assefa, Y., Staggenborg, S.A., Prasad, V.P.V., 2010. Grain sorghum water requirement and responses to drought stress: a review. Crop Manage. 10, 1109–1116.

Awika, J.M., Rooney, L.W., 2004. Sorghum phytochemicals and their potential aspects on human health. Phytochemistry 65, 1199–1221.

Azizian, A., Sepaskhah, A.R., 2014. Maize response to different water, salinity and nitrogen levels: yield–water relation, water-use and water uptake reduction function. Inter. J. Plant Prod. 8, 1735–8043.

Barati, V., Ghadiri, H., Zand-Parsa, S., Karimian, N., 2015. Nitrogen and water use efficiencies and yield response of barley cultivars under different irrigation and nitrogen regimes in a semi-arid Mediterranean climate. Archives Agron. Soil Sci. 61, 15–32.

Bationo, A., Hartemink, A., Lungu, O., Niami, M., Okoth, P., Smaling, P., Thiombiano, L., 2006. African soils – Their productivity and profitability of fertilizer use. Background paper for the Africa fertilizer summit. June 2006, Nigeria.

Blum, A., 2004. Sorghum physiology. In: H. T. Nguyen, and A. Blum, eds. Physiology and Biotechnology Integration for Plant Breeding. Marcel Dekker, New York, NY, pp. 141–223.

Blum, A., 2005. Drought resistance, water-use efficiency, and yield potential—are they compatible, dissonant, or mutually exclusive? Aust. J. Agric. Res. 56, 1159–1168.

Blum, A., 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field. Crop. Res. 112, 119–123.

Blum, A., Arkin, G.F., 1984. Sorghum root growth and water-use as affected by water supply and growth duration. Field Crops Res. 9, 131–142.

Borrell, A.K., Mullet, J.E., George-Jaeggli, B., Van Oosterom, E. J., Hammer, G. L., Klein, P.E., Jordan, D.R., 2014. Drought adaptation of stay–green sorghum is associated with canopy development, leaf anatomy, root growth, and water uptake. J. Exp. Bot. 65, 6251–6263.

Boyer, J.S., 1982. Plant productivity and environment. Science 218, 443–448.

Byerlee, D., Diao, X., Jackson, C., 2005. Agriculture, rural development, and pro-poor growth: Country experiences in the post-reform era. Synthesis paper for the operationalizing pro-poor growth in the 1990s project. Washington DC: The World Bank.

Cairns, J.E., Hellin, J., Sonder, K., Araus, J.L., Macrobert, J.F., Thierfelder, C., Prasanna, B.M., 2013. Adapting maize production to climate change in sub-Saharan Africa. Food Sec. 5, 345–360.

Chauvin, N.D., Mulangu, F., Porto, G., 2012. Food production and consumption trends in Sub–Saharan Africa: Prospects for the transformation of the agricultural sector. United Nations Development Programme (UNDP). Regional Bureau for Africa. WP 2012–011: February 2012.

Chivenge, P., Mabhaudhi, T., Modi, A.T., Mafongoya, P., 2015. The potential role of neglected and underutilised crop species as future crops under water scarce conditions in Sub- Saharan Africa. Int. J. Environ. Res. Public Health 12, 5685–5711.

Clover, J., 2003. Food security in Sub-Saharan Africa. Afr. Security Rev. 12, 5–14.

Comas, L.H., Becker, S.R., Cruz, V.M.V., Byrne, P.F., Dierig, D. A., 2013. Root traits contributing to plant productivity under drought. Front. Plant Sci. 4, 1–13.

Dicko, M.H., Gruppen, H., Traore, A.S., Van Berkel, W.J.H., Voragen, A.G.J., 2005. Evaluation of the effect of germination on phenolic compounds and antioxidant activities in sorghum varieties. J. Agric. Food Chem. 53, 2581–2588.

Dicko, M.H., Gruppen, H., Traore, A.S., Voragen, A., Berkel, W., 2006. Sorghum grain as human food in Africa: relevance of content of starch and amylase activities. Afr. J. Biotechnol. 5, 384–395.

Doorenbos, J., Hassam, A.H., 1979. Yield Response to Water. FAO. Irrigation and Drainage Paper 33. Rome, Italy.

Dotlacil, L., Hermuth, J., Stehno, Z., Dvoracek, V., Bradova, J., Leisova, L., 2010. How can wheat landraces contribute to present breeding? Czech J. Genet. Plant Breed. 46, S70–S74.

Doward, A., Kydd, J., Stockbridge, M., 2004. Agricultural liberalization in Sub Saharan Africa. Inception Report for ECPrep.

Du Plesis, J., 2008. Sorghum production. Department of Agriculture: Republic of South Africa and Agricultural Research Council. pp 1–22.

Dugas, D.V., Monaco, M.K., Olsen, A., Klein, R.R., Kumari, S., Ware, D., Klein, P.E., 2011. Functional annotation of the transcriptome of *Sorghum bicolor* in response to osmotic stress and abscisic acid. BMC Gen. 12, 1–22.

Edmeades, G.O., Beanziger, M., Mickelson, H.R., Pena–Valdivia, C.B., 1997. Developing drought- and low N-tolerant maize. Proceedings of a Symposium, March 25–29, 1996, CIMMYT, El Batan, Mexico. Mexico, D.F.: CIMMYT.

Edmonds, D.E., Abreu, S.L., West, A., Caasi, D.R., Conley, T.O., Daft, M.C., Desta, B.B., England, B., Farris, C.D., Nobles, T.J., Patel, N.K., Rounds, E.W., Sanders, B.H., Shawaqfeh, S.S., Lakmini, L., Manandhar, R., Raun, W.R., 2009. Cereal nitrogen use efficiency in Sub Saharan Africa. J. Plant Nutr. 32, 2107–2122.

Fanadzo, M., Chiduza, C., Mnkeni, P.N.S., Van Der Stoep, I., Stevens, J., 2010. Crop production management practices as a cause for low water productivity at Zanyokwe Irrigation Scheme. Water SA 36, 27–36.

FAO, IFAD and WFP, 2014. The state of food insecurity in the world. Strengthening the enabling environment for food security and nutrition. Rome, FAO.

Fischer, R.A., Byerlee, D., Edmeades, G.O., 2014. Crop yields and global food security: will yield increase continue to feed the world? Canberra: Australian Centre for International Agricultural Research. http://aciar.gov.au/biblio/mn158. (Last accessed on 15 April 2015)

Food and Agriculture Organisation (FAO), 1991. Water and soil requirements. In: W. Critchley, and K. Siegert eds. Water Harvesting (AGL/MISC/17/91) – A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production. http://www.fao.org/docrep/u3160e/u3160e04.htm#2. (Last accessed on 02 May 2015).

Food and Agriculture Organization (FAO), 1995. Sorghum and millets in human nutrition. FAO Food and Nutrition Series, No. 27. Rome, Italy.

Food and Agriculture Organization (FAO), 2008. The state of food and agriculture. Biofuels: prospects, risks and opportunities. Rome, Italy.

Food and Agriculture Organization (FAO), 2010. FAO statistical database. Rome, Italy.

Food and Agriculture Organization (FAO), 2014. Food and nutrition in numbers. Rome, Italy.

Food and Agriculture Organization Statistics (FAOSTAT), 2013. FAO statistical yearbook 2013. World food and agriculture. Rome, Italy.

Galluzi, G., Lopez Noriega, I., 2014. Conservation and use of genetic resources of underutilised crops in the Americas—A continental analysis. Sustainability 6, 980–1017.

Garrity, D., Akinnifesi, F., Ajayi, O., Sileshi, G.W., Mowo, J.G., Kalinganire, A., Larwanou, M., Bayala, J., 2010. Evergreen agriculture: a robust approach to sustainable food security in Africa. Food Sec. 2, 197–214.

Glew, R.H., Vanderjagt, D.J., Lockett, C., Grivetti, L.E., Smith, G.C., Pastuszyn, A., Millson, M., 1997. Amino acid, fatty acid, and mineral composition of 24 indigenous plants of Burkina Faso. J. Food Comp. Anal. 10, 205–217.

Habindavyi, E., 2009. Morphological characterization of sorghum (*Sorghum bicolor*) diversity in Burundi. CBM Swedish Biodiversity Centre, Uppsala University.

Hammer, G.L., Butler, D., Muchow, R.C., Meinke, H., 1996. Integrating physiological understanding and plant breeding via crop modelling and optimisation. In: Cooper, M., Hammer, G.L., (Eds). Plant Adaptation and Crop Improvement. CAB International, ICRISAT & IRRI, Wallingford, UK, pp. 419–441.

Hammer, G.L., Chapman, S.C., Van Oosterom, E.J., Podlich, D.W., 2005. Trait physiology and crop modelling as a framework to link phenotypic complexity to underlying genetic systems. Austr. J. Agric. Res. 56, 947–960.

Hammer, G., Cooper, M., Tardieu, F., Welch, S., Walsh, B., Van Eeuwijk, F., Chapman, S., Podlich, D., 2006. Models for navigating biological complexity in breeding improved crop plants. Trends Plant Sci. 11, 587–593.

Haque, I., Jutzi, S., Neate, P.J.H., eds. 1986: Potentials of forage legumes in farming systems of Sub-Saharan Africa. Proceedings of a workshop held at ILCA, Addis Ababa, Ethiopia, 16–19 September 1985. ILCA, Addis Ababa.

Harris, K., Subudhi, P.K., Borrell, A.K., Jordan, D.B., Rosenow, D., Nguyen, H., Klein, P., Klein, R., Mullet, J., 2006. Sorghum stay-green QTL individually reduce post–flowering drought-induced leaf senescence. J. Exp. Bot. 58, 327–338.

Hensley, M., Botha, J.J., Anderson, J.J., Van Staden, P.P., Du Toit, A., 2000. Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water. WRC Report No. 878/1/00. Water Research Commission, Pretoria, South Africa.

Hulse, J.H., Laing, E.M., Pearson, O.E., 1980. Sorghum and the millets: Their composition and nutritional value, pp. 90. Academic Press, New York, NY, USA.

Ismail, S.M., 2012. Optimizing productivity and irrigation water use efficiency of pearl millet as a forage crop in arid regions under different irrigation methods and stress. Afr. J. Agric. Res. 7, 2509–2518.

Jewitt, G.W.P., Wen, H.W., Kunz, R.P., van Rooyen, A. M., 2009. Scoping study on water use of crops/trees for biofuels in South Africa. Water Research Commission (WRC) report no.1772/1/09.

Kapanigowda, M., Perumal, R., Djanaguiraman, M., Aiken, R.M., Tesso, T., Prasad, P.V.V., Little, C.R., 2013. Genotypic variation in sorghum [*Sorghum bicolor* (L.) Moench] exotic germplasm collections for drought and disease tolerance. SpringerPlus 2, 650–657.

Kebede, H., Subudhi, P.K., Rosenow, D.T., Nguyen, H.T., 2001. Quantitative trait loci influencing drought tolerance in grain sorghum (*Sorghum bicolor* L. Moench). Theor. Appl. Genet. 103, 266–276.

Kijne, J., Barron, J., Hoff, H., Rockstrom, J., Karlberg, L., Gowing, J., Wani, S.P., Wichelns, D., 2009. Opportunities to increase water productivity in agriculture with special reference to Africa and South Asia. A report prepared by Stockholm Environment Institute, for the Swedish Ministry of Environment presentation at CSD 16, New York.

Kim, H.K., Luquet, D., Van Oosterom, E., Dingkuhn, M., Hammer, G., 2010. Regulation of tillering in sorghum: genotypic effects. Annals Bot. 106, 69–78.

Kowieska, A., Lubowicki, R., Jaskowska, I., 2011. Chemical composition and nutritional characteristics of several cereal grain. Acta Sci. Pol. 10, 37–50.

Lafarge, T.A., Broad, I.J., Hammer, G.L., 2002. Tillering in grain sorghum over a wide range of population densities: identification of a common hierarchy for tiller emergence, leaf area development and fertility. Annals Bot. 90, 87–98.

Livingston, G., Schonberger, S., Delaney, S., 2011. Sub-Saharan Africa: The state of smallholders in agriculture. Conference on new directions for smallholder agriculture. IFAD, Rome, Italy.

Mabhaudhi, T., 2009. Responses of maize (*Zea mays* L.) landraces to water stress compared with commercial hybrids. MSc thesis. University of KwaZulu–Natal, Pietermaritzburg, South Africa.

Mabhaudhi, T., Chibarabada, T., Modi, A., 2016a. Water–food–nutrition–health nexus: linking water to improving food, nutrition and health in Sub-Saharan Africa. Int. J. Environ. Res. Public Health 13, 107–136.

Mabhaudhi, T., O'Reilly, P., Walker, S., Mwale, S., 2016b. Opportunities for underutilised crops in Southern Africa's post-2015 development agenda. Sustainability 8, 302.

Machethe, C.L., Mollel, N.M., Ayisi, K., Mashatola, M.B., Anim, F.D.K., Vanasche, F., 2004. Smallholder irrigation and agricultural development in the Olifants river basin of Limpopo province: Management, transfer, productivity, profitability and food security issues. WRC Report No. 1050/1/04. Water Research Commission, Pretoria, South Africa.

Mahgoub, S.E.O., Ahmed, B.M., Ahmed, M.M.O., El Agib, N.N.A., 1999. Effect of traditional Sudanese processing of kisra bread and hulumur drink on their thiamine, riboflavin and mineral contents. Food Chem. 67, 129–133.

Maman, N., Lyon, D.J., Mason, S., Galusha, T.D., Higgins, R., 2003. Pearl millet and grain sorghum yield response to water supply in Nebraska. Agron. J. 95, 1618–1624.

Mativavarira, M., Dimes, J., Masikati, P., Van Rooyen, A., Mwenje, E., Sikosana, J.L.N., Tui, S.H.K., 2011. Evaluation of water productivity, stover feed quality and farmers' preferences on sweet sorghum cultivar types in the semi-arid regions of Zimbabwe. J. SAT Agril. Res. 9, 1–9.

Matsumoto, S., Tsuboi, T., Asea, G., Maruyama, A., Kikuchi, M., Takagaki, M., 2014. Water response of upland rice varieties adopted in Sub-Saharan Africa: a water application experiment. J. Rice Res. 2, 1–6.

Mavhura, E., Manatsa, D., Mushore, T., 2015. Adaptation to drought in arid and semi-arid environments: case of the Zambezi Valley, Zimbabwe. Jamba: J. Disast. Risk Stud. 7, 1–7.

McKevith, B., 2004. Nutritional aspects of cereals. British nutrition foundation. Nutri. Bulletin 29, 111–142.

Mokh, F.E., Nagaz, K., Masmoudi, M.M., Mechlia, N.B., 2013. Soil salinity and water productivity of carrot–millet system as influenced by irrigation regimes with saline water in arid regions of Tunisia. J. Agric. Envir. Inter. Dev. 107, 179–199.

Morris, G.P., Ramu, P., Deshpande, S.P., Hash, C.T., Shah, T., Upadhyaya, H.D., Riera-Lizarazu, O., Brown, P.J., Acharya, C.B., Mitchell, S.E., Harriman, J., Glaubitz, J.C., Buckler, E.S., Kresovich, S., 2013. Population genomic and genome-wide association studies of agroclimatic traits in sorghum. Proc Natl Acad Sci 110, 453–458.

Mwadalu, R., Mwangi, M., 2013. Potential role of sorghum in enhancing food security in semi-arid eastern Kenya. J. Appl. Biosci. 71, 5786–5799.

Ofori, E., Oteng-Darko, P., Berchie, J.N., Nimako, F.O., Yeboah, S., Danquah, E.O., 2014. Monitoring of soil moisture regime and water use efficiency under maize cowpea cropping system. Int. J. Curr. Microbiol. App. Sci. 3, 837–848.

Oot, D.A, Hicks, J., Borton, N., 1996. Lost crops of Africa, Volume I, Grains. Board on Science and Technology for International Development. National Research Council, National Academy Press, Washington, D.C., USA.

Orr, A., Mwema, C., Gierend, A., Nedumara, S., 2016. Sorghum and millets in eastern and southern Africa. Facts, trends and outlook. Working Paper Series No. 62. ICRISAT Research Program, Markets, Institutions and Policies. Patancheru 502324, Telangana, India: International Crops Research Institute for the Semi-Arid Tropics. pp 76.

Ortiz, R., Iwanaga, M., Reynolds, M.P., Wu, H., Crouch, J., 2007. Overview on crop genetic engineering for drought prone environments. J. Semi-Arid Tropic. Agric. Res. 4, 1–30. http://ejournal.icrisat.org/SpecialProject/sp3.pdf

Padulosi, S., Eyzaquirre, P., Hodgkin, T., 1999. Challenges and strategies in promoting conservation and use of neglected and underutilised crop species, in: Janick, J., (Ed). Perspectives on New Crops and New Uses. ASHS Press, Alexandria, VA, USA. pp. 140–145.

Padulosi, S., Hoeschle–Zeledon, I., Bordoni, P., 2008. Minor crops and underutilised species: lessons and prospects, in: Maxted, N., Ford-Lloyd, B.V., Kell, S.P., Iriondo, J.M., Dulloo, M.E., Turok, J., (Eds). Crop Wild Relative Conservation and Use. CAB International, Wallingford, UK. pp. 605–624.

Padulosi, S., Heywood, V., Hunter, D., Jarvis, A., 2011. Underutilised species and climate change: Current status and outlook, in: Yadav, S.S., Redden, R.J., Hatfield, J.L., Lotze-Campen, H., Hall, A.E., (Eds). Crop Adaptation to Climate Change, 1st ed. Blackwell Publishing Ltd, Oxford, UK. pp. 507–521.

Pandravada, S.R., Sivaraj, N., Sunil, N., Jairam, R., Prasanthi, Y., Chakrabarty, S.K., Ramesh, P., Bisht, I.S., Pareek, S.K., 2013. Sorghum landraces patronized by tribal communities in Adilabad district, Andhra Pradesh. Ind. J. Tradition. Know. 4, 465–471.

Ragaee, S., Abdel-Aal, E.M., Noaman, M., 2006. Antioxidant activity and nutrient composition of selected cereals for food use. Food Chem. 98, 32–38.

Ringler, C., Zhou, T., Koo, J., Wang, D., 2010. Climate change impacts on food security in Sub-Saharan Africa. Insights from comprehensive climate change scenarios. IFPRI Discussion Paper 01042.

Rizhsky, L., Liang, H., Mittler, R., 2002. The combined effect of drought stress and heat shock on gene expression in tobacco. Plant Physiol. 130, 1143–1151.

Robertson, M.J., Fukai, S., Hammer, G.L., 1993. Water extraction by grain sorghum in a sub-humid environment. I. Analysis of the water extraction pattern. Field Crops Res. 33, 81–97.

Romney, D.L., Thorne, P., Lukuyu, B., Thornton, K., 2003. Maize as food and feed in intensive smallholder systems: management options for improved integration in mixed farming systems of east and southern Africa. Field Crops Res. 84, 159–168.

Rooney, L.W., 2007. Food and nutritional quality of sorghum and millet. INTSORMIL 2007 Annual Report, Lincoln, Nebraska, USA. pp. 91–93.

Rosenow, D.T., Clark, L.E., 1995: Drought and lodging resistance for a quality sorghum crop. In: Proceedings of the 5th annual corn and sorghum industry research conference (Chicago, IL, 6–7 December 1995), American Seed Trade Association, Chicago, IL. pp 82–97.

Rosenow, D.T., Ejeta, G., Clark, L.E., Gilbert, M.L., Henzell, R.G., Borrell, A.K., Muchow, R.C., 1996. Breeding for pre and post-flowering drought stress resistance in sorghum, in: Rosenow, D.T., Yohe, J.M., (Eds). Proceedings of the International Conference on Genetic Improvement of Sorghum and Pearl Millet. (Lubbock, TX, 22–27 September 1996), ICRISAT, Lubbock, India. pp. 400–411.

Rosenow, D.T., Dalhberg, J.A., 2000. Collection, conversion and utilization of sorghum, in: Smith, C.W., Frederiksen, A.R., (Eds). Sorghum, Origin, History, Technology and Production: Wiley Series in Crop Science. John Wiley and Sons, New York, USA. pp 309–328.

Saneoka, H., Ogata, S., 1987. Relationship between water use efficiency and cuticular wax deposition in warm season forage crops grown under water deficit conditions. Soil Sci. Plant Nutr. 33, 439–448.

Schittenhelm, S., Schroetter, S., 2014. Comparison of drought tolerance of maize, sweet sorghum and sorghum–sudangrass hybrids. J. Agron. Crop Sci. 200, 46–53.

Schmidhuber, J., Tubiello, F.N., 2007. Global food security under climate change. Proc. Natl Acad. Sci. 104, 19703–19708.

Schulze, R. E., 2011. Approaches towards practical adaptive management options for selected water related sectors in South Africa in a context of climate change. Water SA 37, 621–646.

Sebastian, K., 2009. Agro-ecological zones of Africa. International Food Policy Research Institute. Washington, DC.

Sheorain, V., Banka, R., Chavan, M., 2000. Ethanol production from sorghum, in: Chandrashekar, A., Bandyopadyay, R., Hall, A.J., (Eds). Technical and Institutional Options for Sorghum Grain Mold Management: Proceedings of an International Consultation. 18–19 May 2000. ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), Patancheru, India. pp. 228–239.

Singh, P., Wani, S.P., Pathak, P., Sahrawat, K.L., Singh, A.K., 2011. Increasing crop productivity and effective use of water in rainfed agriculture, in: Boelee, E., (Ed). Integrated Watershed Management in Rainfed Agriculture. CRC Press (Taylor & Francis), London, UK. pp. 315–347.

Sonobe, K., Hattori, T., An, P., Tsuji, W., Eneji, A.E., Kobayashi, S., Kawamura, Y., Tanaka, K., Inanaga, S., 2011. Effect of silicon application on sorghum root responses to water stress. J. Plant Nutr. 34, 71–82.

Steduto, P., Hsiao, T.C., Fereres, E., 2007. On the conservative behavior of biomass water productivity. Irri. Sci. 25, 189–207.

Takele, A., Farrant, J., 2013. Water relations, gas exchange characteristics and water use efficiency in maize and sorghum after exposure to and recovery from pre and post–flowering dehydration. Afr. J. Agric. Res. 8, 6468–6478.

Taylor, J.R.N., 2003. Overview: Importance of sorghum in Africa. In Proceedings of AFRIPRO Workshop on the proteins of sorghum and millets: Enhancing nutritional and functional properties for Africa, Vol. 9. Pretoria, South Africa.

Tolk, J.A., Howell, T.A., Miller, F., 2013. Yield component analysis of grain sorghum grown under water stress. Field Crops Res. 145, 44–51.

Tsuji, W., Ali, M.E.K., Inanaga, S., Sugimoto, Y., 2003. Growth and gas exchange of three sorghum cultivars under drought stress. Biologia Planta. 46, 583–587.

Tsuji, W., Shinobu, I., Hideki, A., Shigenor, M., An, P., Sonobe, K., 2005. Development and distribution of root system in two grain sorghum cultivars originated from Sudan under drought stress. Plant Prod. Sci. 8, 553–562.

Vadez, V., 2014. Root hydraulics: the forgotten side of roots in drought adaptation. Field Crops Res. 165, 16–24.

Van Oosterom, E.J., Chapman, S.C., Borrell, A.K., Broad, I.J., Hammer, G.L., 2010. Functional dynamics of the nitrogen balance of sorghum II. Grain filling period. Field Crops Res. 115, 29–38.

Virupakshagowda, C.`P., A. A. Khalid, M. Rangaswamy, H. M. T. El-Kamil, M. Samy, A. Ali, M. B. Chandrashekhar, and H. G. Prasanna, 2015: Assessing agricultural water productivity in desert farming system of Saudi Arabia. IEEE J. Select. Topics Appl. Earth Obs. Remote Sens. 8, 284–297.

Wang, Y., Wang, D., Shi, P., Omasa, K., 2014. Estimating rice chlorophyll content and leaf nitrogen concentration with a digital still color camera under natural light. Plant Methods 10, 1–11.

Water Research Commission (WRC) 2014. WRC Knowledge Review 2013/14. Project No. K5/2274//4 Determining water use of indigenous grain and legume food crops. Pretoria, South Africa.

Williams, J.T., Haq, N., 2002. Global research on underutilised crops. An assessment of current activities and proposals for enhanced cooperation. International Centre for Underutilised Crops (ICUC), Southampton, UK.

Williams, S.B., Gray, S.J., Laidlaw, H.C.K., Godwin, I.D., 2012. Particle inflow gun-mediated transformation of *Sorghum bicolor*, in: Curtis, I.S., (Ed). Transgenic Crops of the World: Essential Protocols. Kluwer Academic Publishers, Dordrecht, Netherlands. pp. 89–101.

World Bank, 2008. World development report 2008: Agriculture for development. The World Bank, Washington, DC.

World Development Indicators (WDI), 2015. Data – The World Bank. (WDI) http://knoema.com/atlas/ranks/Land-undercereal-production?baseRegion=BW. (Last accessed on 12 June 2015).

Yetneberk, S., De Kock, H.L., Rooney, L.W., Taylor, J.R.N., 2004. Effects of sorghum cultivar on injera quality. Cereal Chem. 81, 314–321.

Yihun, Y.M., Haile, A.M., Schultz, B., Erkossa, K., 2013. Crop water productivity of irrigated teff in a water stressed region. Water Resour. Manage 27, 3115–3125.

Zhang, H., Oweis, T., Garabet, S., Pala, M., 1998. Water use efficiency and transpiration efficiency of wheat under rain-fed and irrigation conditions in Mediterranean environment. Plant Soil 201, 295–305.

Zhang, Y., Tang, Q., Peng, S., Xing, D., Qin, J., Laza, R.C., Punzalan, B.R., 2012. Water use efficiency and physiological response of rice cultivars under alternate wetting and drying conditions. Sci. World J. 2012, 1–10.

Zhao, C.-X., He, M.-R., Wang, Z.-L., Wang, Y.-F., Lin, Q., 2009. Effects of different water availability at post-anthesis stage on grain nutrition and quality in strong–gluten winter wheat. C. R. Biologies 332, 759–764.

Zingore, S., 2011. Maize productivity and response to fertilizer use as affected by soil fertility variability, manure application, and cropping system. Better Crops 95, 4–6.

Zwart, S.J., Bastiaanssen, W.M., 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agric. Water Manag. 69, 115–133.

CHAPTER 3

DROUGHT TOLERANCE AND WATER USE OF GRAIN LEGUMES

Chibarabada, T.P., Modi, A.T. and Mabhaudhi, T.

3.1. Introduction

Water scarcity is increasing and this is exacerbated by population growth and ongoing climate variability and change (Conway et al., 2009). Most of the regions categorized as 'water scarce' lie in the semi-arid and arid tropics. It is also in these regions that approximately 70% of the population depends on agriculture for their food and livelihood (Alliance for a Green Revolution in Africa (AGRA), 2013; Graeub et al., 2015). The prevalence of food and nutritional insecurity in semi-arid and arid tropics also remains high. South Asia and sub-Saharan Africa (SSA) have the highest estimated number of individuals experiencing some form of undernutrition (281 million and 224 million, respectively) (FAO et al., 2015). This represents about 15% and 23% of the respective populations of South Asia and SSA. These figures are expected to increase due to population growth and climate change. The 2014/15 and 2015/16 drought that was experienced across SSA due to El Niño placed more than 30 million people at risk of hunger, with children being most vulnerable (UNICEF, 2015). There is a need for a paradigm shift in terms of how we address challenges of food and nutrition security (Mabhaudhi et al., 2016). Part of this includes identifying and promoting the cultivation of crops that are most suited to these environments. Such crops should also have the inherent capacity to contribute to the resilience of farming systems in these areas.

Across much of the semi-arid and arid tropics, cereals (rice (*Oryza sativa*), maize (*Zea mays*) and wheat (*Triticum spp*.) and root and tuber crops (cassava (*Manihot esculenta*)), Irish potato *(Solanum tuberosum*) and sweet potato (*Ipomea batatas*) are the staple crops. These crops have been the subject of significant research and government attention (OECD and FAO, 2015). This has led to breeding of high-yielding and drought-tolerant cultivars of common cereals and root and tuber crops. Cereals and root and tuber crops, which are starch rich, mainly provide calories to address energy requirements but lack dietary diversity to ensure adequate nutrition (Kearney, 2010). Dietary diversity is a strategy that involves including a variety of food groups to the diet such as fruit and vegetables, legumes, starch and animal products (Faber et al., 2002). Meat, fruit and vegetables are the major sources of proteins and micronutrients, respectively, but they are not always accessible to the rural poor. Meat remains expensive while fruit and vegetables are generally affordable, only when in season, but unaffordable when out of season. In this regard, the use of grain legumes as alternative sources of protein and other micronutrients (Iqbal et al., 2006) could assist in improving dietary diversity of poor rural households.

The promotion of grain legumes has been mainly linked to them being rich sources of protein, low in saturated fat, as well as possessing certain important micronutrients (zinc, folate and calcium and tocopherols) (Akinyele and Shokunbi, 2015; Boschin and Arnoldi, 2011; Seena and Sridhar, 2005). In this regard, legumes could contribute significantly to diets of rural households if consumed as compliments to starch. While history shows that early Khoikhoi and Indian settlers in the semi-arid and arid tropics utilized indigenous legumes as a major component of their diets (Mooney and Drake, 2012), this status has since changed. The "Green Revolution" shifted attention to cereal crops. While this resulted in improvements to crop production and energy supply, it inadvertently resulted in stagnation of production and crop improvement of legumes (Pingali, 2012). The promotion of legumes, which are adapted to the semi-arid and arid tropics, will contribute to the diversity of cropping systems and diets of people living in these areas. However, there is need to address critical knowledge gaps that will allow for the promotion and reinstatement of legumes within food systems.

To date, there have been separate attempts by crop scientists (Chibarabada et al., 2015; Mabhaudhi et al., 2013; Muñoz-Perea et al., 2007; Obalum et al., 2011; Patel et al., 2008; Siddique et al., 2001; Zhang et al., 2000) and nutritionists (Akinyele and Shokunbi, 2015; Boschin and Arnoldi, 2011; Seena and Sridhar, 2005) to address the knowledge gap on legumes. These efforts have been disciplinary and the information is yet to be consolidated to make meaningful impact on policy. The emerging interest in minor legumes, indigenous to semi-arid and arid tropics, should also be considered (Chivenge et al., 2015). As the world celebrated the International Year of Pulses in 2016, there was a need to re-conceptualize the possible role that legumes can play in the post-2015 agenda. The aim of this review was to provide a holistic perspective on the potential of legumes. This was done through focusing on the legume value chain and identifying challenges and opportunities for unlocking the value of legumes.

A mixed-method review approach, which included combining quantitative and qualitative research or outcomes with process studies, was used to compile the review. Scientific journal articles, book chapters, technical reports and other forms of literature were used for the review. The review focused primarily on literature describing sub-Saharan Africa and South Asia; the two regions share similar development trajectories, challenges and opportunities, thus making them comparable. The review was then structured as follows; Section 3.2 provides an overview of water scarcity in SSA and SA and its effect on agricultural production. Furthermore, Section 3.2 also highlights food and nutritional security status in SSA and SA using selected indicators such as stunting, wasting, anaemia and obesity. Section 3.3 discusses grain legumes, with a focus on their diversity and adaptability to the semi-arid and arid tropics. Section 3.4 discusses the progress and gaps in research on grain legumes. A value chain approach was used to categorize research into four components, namely, (i) breeding and crop improvement; (ii) agronomy; (iii) processing and utilization; and (iv) marketing. Lastly, Sections 3.5 and 3.6 present the challenges, opportunities and recommendations concerning promoting legumes in semi-arid and arid tropics.

3.2 Setting the Scene – South Asia and Sub-Saharan Africa

South Asia refers to the southern part of Asia, which is dominated by the Indian tectonic plate that rises above sea level as Nepal and extends to the south of the Himalayas and the Hindu Kush. Sub-Saharan Africa refers to the regions that are fully or partially located south of the Sahara Desert. The two regions are climatically alike according to the Köppen-Geiger climate classification. They are described as semi-arid and arid climates due to actual precipitation being less than actual evapotranspiration (Peel et al., 2007). These two regions are also considered the poorest regions in the world (Wojcicki, 2014). Approximately 70% of the population in these regions reside in rural areas and rely on agriculture for their food and livelihood (www.worldbank.org). However, agricultural activities are challenged primarily by water scarcity.

3.2.1 Water Scarcity

Most countries in South Asia and sub-Saharan Africa experience some form of water scarcity (Fig 3.1). Rainfed agriculture is the primary source of food production in the semi-arid and arid tropics. The amount of arable land under rain-fed production ranges from 60% to 95% (Rockström et al., 2010); making water is the most limiting factor in crop production. The uncertainties in rainfall distribution and occurrences and the high frequency of dry spells and droughts (Rockström, 2003) frequently result in significant yield losses and crop failure for rural farmers. Most of them are incapable of recovering from such disturbances. This alludes to the importance of promoting resilient cropping systems in these areas.

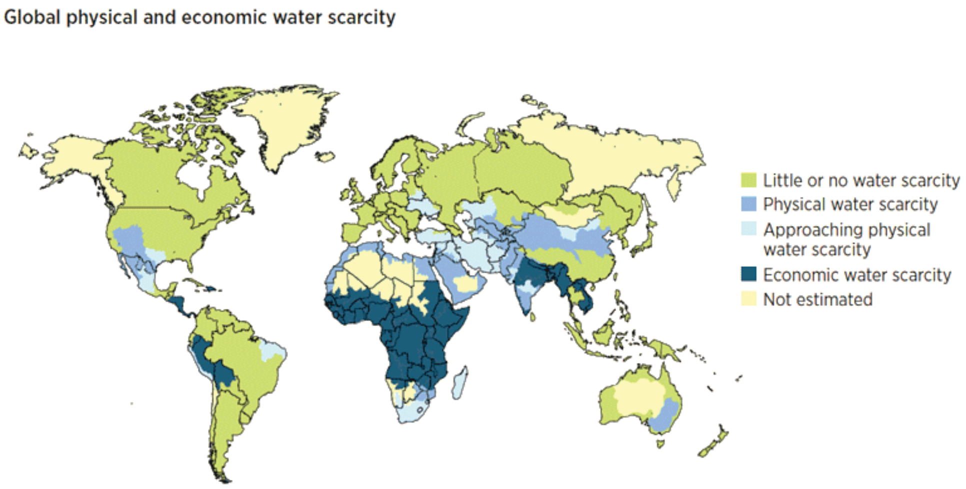

Figure 3.1: Areas of physical and economical water scarcity on a basin level in 2007 (Molden, 2007). Most of the regions categorized as 'water scarce' fall in semi-arid and arid tropics.

3.2.3 Food and Nutritional Insecurity in Semi-arid and Arid Tropics

Agriculture is the major livelihood activity for 70% of people residing in the semi-arid and arid regions (Graeub et al., 2015; Rockström, 2003). Food production is often inadequate to meet household food and nutrient requirements; hence, people still must buy food despite it being unaffordable (Molden, 2007). This may in part explain the high prevalence of food and nutritional insecurity. South Asia and sub-Saharan Africa are faced with the highest prevalence of malnutrition (under- and over-nutrition) in the world (IFPRI, 2014). Undernutrition is commonly in the form of stunting (low height for age), wasting (low weight for age) and underweight in children under five years old (International Food Policy Research Institute, n.d.). It is estimated that one-half to two-thirds of stunted, wasted and underweight children reside in South Asia while one-third reside in sub-Saharan Africa (UNICEF et al., 2014). This implies that 80% to 90% of the world's undernourished children reside in the semi-arid and arid tropics. In addition, prevalence of micronutrient deficiencies is high with anaemia (a condition caused by lack of iron) having the highest prevalence affecting at least 50% of women in the reproductive age (IFPRI, 2014). Conversely, being overweight and obesity affect at least 30% of the population (Wojcicki, 2014). These high levels of malnutrition are symptomatic of the poor dietary diversity in semi-arid and arid tropics. Based on these statistics, it is evident that nutrient intakes are not balanced (Mabhaudhi et al., 2016) to meet the requirements for a healthy life – food and nutritional security.

Food security was defined as a 'situation when all people at all times have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life' (FAO, 1996). This definition was not properly translated into regional agricultural policies, which led to a prioritization of food production over nutrition agendas. To emphasize the nutrition aspects and to clearly differentiate dietary quantity and quality, this review uses the term 'food and nutrition security' (Shetty, 2015; Thompson et al., undated). Agriculture, as the main source of food and livelihood in semi-arid and arid regions, provides an appropriate platform to tackle food and nutritional insecurity (Graeub et al., 2015; McDermott et al., 2015; Shetty, 2015). This can be achieved, in part, by increasing crop diversity and improving crop productivity, which in turn strengthens the pillars of food and nutritional security. Furthermore, any such efforts should be defined and designed taking into consideration limitations posed by water scarcity i.e., recognizing the water-food-nutrition-health nexus (Mabhaudhi et al., 2016). This includes the promotion of crops that are adapted to dry areas and are nutrient dense (Mabhaudhi et al., 2016) such as legumes (Chivenge et al., 2015).

Previous food security initiatives in semi-arid and arid regions had a narrow focus of increasing production of cereals and root and tuber staple crops. Consequently, such staple crops currently occupy 70% of arable crop area. Although these staples have a role to play in providing daily energy requirements, they are often poor sources of other nutrients. This poses concerns on dietary diversity and could be partly why semi-arid and arid regions are faced with the burden of malnutrition. There is need for a balance between starch-rich foods and other nutrient dense foods to improve dietary diversity. According to Alleyne et al. (1977), one of the major concerns in diets of the rural poor is the issue of protein energy malnutrition. Legumes are a good source of protein and micronutrients and hence could be a good compliment to starchy diets (Abberton, 2010).

Khan (1987) reported daily per capita consumption of grain legumes to be 30 to 40 g in SSA and 40 to 60 g in SA. While in SA, consumption is higher than in SSA, both regions are comparatively lower when compared to the world daily per capita consumption of 65 g. This is exacerbated by the fact that consumption of animal-based protein in both SSA and SA is also lower (20 g daily per capita consumption) compared to the world (34 g daily per capita consumption) (Singh and Singh, 1992). This highlights the poor protein diets in semi-arid and arid regions. Animal-based protein is expensive; hence, there is more scope to increase protein in diets by increasing consumption levels of grain legumes.

3.3 Grain Legumes

3.3.1 Taxonomy

The word legume derives from the Latin word 'legere' that means 'to gather' (Hatcher and Battey, 2011). Legume refers to the fruit of plants that are usually gathered by hand. Legumes belong to the Fabaceae family and have an estimated 18,000 species in about 650 genera making them the third largest group of plant families after Orchidiacea and Compositae. The Fabaceae family comprises three sub-families Caesalpinioideae, Mimosoideae and Papilionoideae, depending on floral structure. The former two each comprise five tribes, which are mostly ornamental plants. The sub-family Papilionoideae comprises more than 32 tribes making it the biggest and most diverse sub-family; all grain legumes and major forage species belong to this sub-family. Of the 32 tribes, only seven tribes are edible (Allen and Allen, 1981) (Table 3.1); these form the focus of this review.

Table 3.1: Taxonomic affinities (tribe, subtribe, species and common names) of grain legumes.

Tribe	Sub-Tribe	Species	Common Name
Dalbergieae		*Arachis hypogaea* L.	groundnut
Cicerea		*Cicer arietum* L.	chickpea
Viciaea		*Lens culinaris* Med	lentil
		Pisum sativum L.	common pea
		Vicia faba L.	fababean
		Lathyrus sativus L.	grass pea
Genisteae	Lupininae	*Lupinus albus* L.	white lupine
		L lueus L.	yellow lupine
		L angustifolius L.	blue lupine
		L. mutabilis Sweet.	tarwi, chocho,
Phaseoleae	Erythrininae	*Mucana* spp. (velvet beans)	velvet beans
	Diocleinae	*Canavalia ensiformis* (L.) DC.	jackbean
		C. gladiata (Jacq.) DC.	swordbean
		Pachyrrhizus erosus (L.) Urban	yam bean
		P. tuberosis (Lam.) Spreng.	yam bean
		Calopogonium mucuniodes Desv	wild groundnut
	Glycininae	*Pueraria phaseoloides* (Roxb.) Benth.	puero, tropical kudzu
		Glycine max (L.) Merr.	soybean
	Clitoriinae	*Centrosema pubescens* Benth.	butterfly pea
		Clitoria ternatea L.	butterfly pea
	Phaseolinae	*Psophocarpus tetragonolobus* (L.) DC.	winged bean
		Lablab purpureus (L.) Sweet	lablab
		M. uniflorum (Lamb.) Verdc	horse gram, kulthi bean, hurali,
		Vigna aconitifolia (Jacq.) Marechal	moth bean
		V. angularis (Willd.)	azuki bean
		V. mungo (L.) Hepper	mung bean
		V. radiate (L.) Wilczek	mung bean
		V. subterranea (L.) Verdc.	bambara groundnut
		V. umbellate (Thunb.)	rice bean
		V. unguiculata (L.) Walp	cowpea
		Phaseolus acutifolus A. Gray	tepary bean
		P. coccineus L.	runner bean
		P. lunatis L.	lima bean
		P. polyanthus Greenm.	polyanthus bean
		P. vulgaris L.	common bean
	Cajaninae	*Cajanus cajan* (L.) Millsp.	pigeon pea
Indigoferae		*Cyamopsis tetragonoloba* (L.) Taubert	cluster-bean, siam-bean
Crotalariaea		*Crotalaria juncea* L.	indian hemp, sun hemp

3.3.2 Ecology

The highly diverse species of grain legumes are indigenous to various parts of the world. The ecology is largely influenced by climate of its centre of diversity (Allen and Allen, 1981; Smartt, 1990). The main centres of diversity are Central America, South America, south-western America, Africa and Europe. Owing to their wide diversity, grain legumes can be grown across different rainfall areas ranging from 200 mm to 1500 mm (Table 3.2). As such, some grain legumes are suited to the semi-arid and arid tropics that receive low annual rainfall. Although they grow well in environments similar to that of their centre of diversity, they also adapt to other environments (Smartt, 1976) implying that they have wide adaptability.

Depending on species as well as season and cultivar, grain legumes take between 60 to 200 days to mature, making them suitable crops for sequential cropping (Table 3.2). Semi-arid and arid tropics are faced with uncertainties in rainfall distribution and occurrences as well as high frequency of dry spells which short season crops may be able to escape. Grain legumes are not associated with tolerance to waterlogging and frost. This poor adaptability can be attributed to the centres of diversity being mild environments. Several grain legumes are short-day plants, an attribute owing to their centres of diversity, with a few exceptions such as white lupine, chickpea, lentil and common pea being long-day plants (Table 3.2). There are, however, bred short-day cultivars of white lupine, chickpea, lentil and common pea. Average grain yield ranges from 300 to 14,000 $kg \cdot ha^{-1}$ depending on season, crop species, cultivar and management practices (Table 3.2). The low yield in some grain legumes, relative to cereals and root and tuber crops, has been suggested as a possible reason for their decline in rural cropping systems. However, grain legumes can offer other ecological benefits that cereal crops cannot.

One distinct ecological function that makes grain legumes unique is their ability to fix atmospheric nitrogen (Allen and Allen, 1981). While the Roman and Egyptian early settlers observed that in the presence of legume species soil was somewhat nutrient rich and plants were greener, it was only in 1888 when German scientists discovered that it was the legume root nodule that was responsible for this (Sur et al., 2010). Since then, this made grain legume crops of particular interest in faming systems, especially under marginal conditions (Crews and Peoples, 2004; Hutchinson, 1969; Zahran, 1999).

Table 3.2: Ecological characteristics (temperature, rainfall, growth cycle, photoperiod, soil type and yield) of selected grain legumes from the seven tribes of grain legumes.

Species	**Min, Max temp (°C)**	**Annual Rainfall (mm)**	**Growth Cycle (days)**	***Photoperiod**	**Soil type**	**Grain Yield (kg ha^{-1})**	**Source**
Dry bean	10, 30	600 - 650	70 - 200	Short day	Sandy loam to heavy clays	500 - 2,500	(www.nda.agric.za)
Groundnut	10,30	500 - 600	125 - 150	Short day	Sandy loam	800 - 3,500	(Smartt, 2012)
Chickpea	5,25	400 - 600	84 - 125	Long day	Sandy to silt loam	630 - 850	(www.nda.agric.za)
Soybean	10, 25	500 - 900	120 - 130	Short day	Clay loam	2,000 - 4,000	(Dugje et al., 2009)
Lablab	10, 35	700 - 1,500	60 - 120	Short day	Deep sands to heavy clays	1,000 - 2,500	(Valenzuela and Smith, 2002)
Cowpea	8, 35	400 - 700	70 - 150	Short day	Sandy	1,000 - 2,000	(Dugje et al., 2009)
Bambara groundnut	10, 35	400 - 600	90 - 180	Short day	Sandy loam	300 - 3,000	(Swanevelder, 1998)
Pigeon pea	–	–	100 - 200	Short day	Sandy to silt loam	718 - 1,080	(Odeny et al., 2007)
Tepary bean	20, 48	200 - 600	60 - 120	Short day	Sandy loam	1,410 - 2,239	(Hamama and Bhardwaj, 2002)
Common Pea	5, 22	350 - 500	55 - 75	Day neutral	Sandy loam	1,500 - 3,120	(Boswell, 1926)
Faba bean	-2, 25	700 - 1,200	110 - 130	Short day	Clay loam	2,000 - 14,000	(Www.dpi.nsw.gov.au
White lupine	-7, 15	381 - 990	116 - 130	Long day	Sandy to silt loam	1,570	(USDA)

*Photoperiod: Short day = 10 hours or less; Day neutral = 10 to 12 hours; Long Day = 12 hours or more.

3.3.3. Major vs. Minor Grain Legumes

There is a wide diversity of grain legume species and there are concerns that some species are more prominent compared to others in terms of breeding efforts, socioeconomic importance, area under cultivation and utilization. This dichotomy is often referred to in the literature as major and minor grain legumes. Other terms also used to refer to minor grain legumes are underutilised, neglected, orphan, promising and future grain legumes. There still lacks a consensus definition of underutilised, neglected or minor grain legumes. The lack of a consensus definition of major vs. minor legumes creates challenges when attempting to categorize legumes. Congenial examples would be of chickpea and cowpea where their underutilization is geographically distributed. Cowpea used to be widely used but now it is only common in African diets and its use is slowly diminishing in other areas.

In this review, we define major grain legumes as those species that are recognized internationally regardless of their centres of diversity, occupy significant crop area, have been subject to formal crop improvement and research and have common and established value chains internationally. Minor grain legumes are those that are only of regional importance, are neglected or underutilised in any dimension (geographic, social and economic) and have no common international and established value chain.

3.4 Legume Value Chain

Approximately 30-grain legumes are grown in the semi-arid and arid tropics across different ecological niches. Chickpea, dry bean, groundnut, pigeon pea, cowpea and soybean account for more than 90% of grain legume production (Table 3.3). The remainder of the grain legumes (e.g., fababean, bambara groundnut, common pea and lablab, lentil) account for less than 10% of legume production (Abate et al., 2012). Singh and Singh (Singh and Singh, 2014) reported that in the last ten years there had been a significant upward trend (≈6%) in production of lentil in SA. Table 3.3 highlights the production trends of major and minor grain legumes where dry bean, groundnut and soybean are popular (each occupying > 5 million ha of land) across all regions and cowpea and chickpea are only popular in SSA and SA, respectively. In semi-arid and arid tropics, more than 95% of grain legumes are produced under dryland conditions (Oweis, 1997). This implies that there is scope to increase grain legume production without increasing water withdrawals. This would be mostly through improvements in water productivity.

In semi-arid and arid tropics, legumes are planted on approximately 60 million hectares of land. This figure is minute when compared to starchy crops (cereals and root and tuber crops) that occupy over 250 million hectares in the same regions (Table 3.3). Starchy crops, as staple crops, have benefited from research related to their breeding, production, utilization and marketing. In this review, these components are referred to as a 'research value chain.' The 'research value chain' concept is used to describe the research activities and various stakeholders that products go through for them to be made available to consumers. The research value chain concept also extends to describe the value that products add to consumers and how they have been marketed and made available to consumers (Fig 3.2).

Starchy crops have established value chains and, owing to this high production, are widely available and utilized. If grain legumes are to be promoted, it is also imperative that research is carried out across the various points within a value chain. This review provides an overview of the grain legume research value chain to date. This will aid in identifying opportunities and constraints that exist for the promotion of grain legumes in rural farming systems of semi-arid and arid tropics.

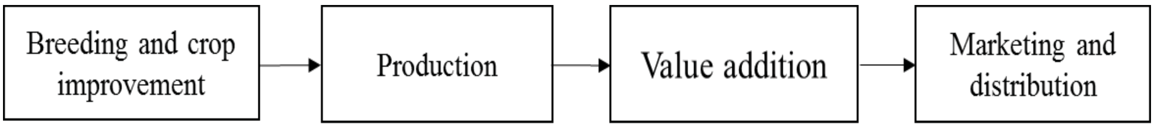

Figure 3.2: Research value chain from breeding and crop improvement to marketing and distribution.

Table 3.3: Production trends of selected grain legumes (chickpea, dry bean, groundnut, pigeon pea, soybean and cowpea) in the world and semi-arid and arid tropics (sub-Saharan Africa, and South Asia) for the period 2010–2012 (Adapted from Abate et al. (2012) and Nedumaran et al. (2015) with some minor modifications from faostat.fao.org).

	Area (1000 ha)	Yield (kg·ha^{-1})	Production (1000 Metric Ton)	% of World Production
World				
Chickpea	10,914	818	8929	-
Dry bean	27,232	723	19,705	-
Cowpea	14,500	454	6155	-
Groundnut	22,633	1607	36,379	-
Pigeon Pea	4655	885	3463	-
Soybean	92,622	2348	217,397	-
Lentil	3571	1904	2900	-
Sub-Saharan Africa				
Chickpea	398	769	315	3.5
Dry bean	5190	596	3045	16
Cowpea	11,440	450	5145	84
Groundnut	9057	1007	8942	40
Pigeon Pea	499	729	363	10
Soybean	1228	1060	1279	1.3
Lentil	100	1094	90	2
South Asia				
Chickpea	8334	855	6792	76
Dry bean	11,532	985	5908	30
Cowpea	159	975	154	3
Groundnut	7038	1122	8457	31
Pigeon Pea	4118	840	3068	88
Soybean	8490	1275	5735	9.2
Lentil	1700	633	1088	33

3.4.1 Breeding and Crop Improvement

Progress in breeding and crop improvement has been relatively slow, especially when compared to cereals such as maize, rice and wheat. Since the 1970s, grain legume breeding focused on disease resistance, growth habit and duration in relation to increasing yields (Oppen, 1981). It was only post-2000 that characteristics such as drought and heat-stress tolerance and environmental adaptability (genotype × environment) became topical (Duc et al., 2015; Sharma et al., 2013). Recently, pre-breeding of some minor grain legumes indigenous to semi-arid and arid tropics (e.g., cowpea, pigeon pea, and chickpea) has come into light for their adaptation to drought and heat stress.

Consultative Group on International Agricultural Research (CGIAR) institutes such as the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), International Institute of Tropical Agriculture (IITA), and the Centre for Agricultural Research in Dry Areas

(ICARDA) have largely driven breeding and crop improvement of grain legumes for the semi-arid and arid tropics. This is with the exception of soybean breeding and crop improvement that has also been driven by private seed companies. Consultative Group on International Agricultural Research institutes are also responsible for germplasm conservation with ICRISAT and IITA maintaining the highest number of grain legume accessions. ICRISAT maintains 14,968 accessions of groundnut, 13,771 of pigeon pea and 81,000 of chickpea (www.icrisat.org) while IITA maintains 15,115 accessions of cowpea, 1742 of soybean, 1815 of bambara groundnut and ≈2000 of other minor grain legumes combined (www.iita.org). It is interesting to note that despite the large germplasm collections, <1% has so far been utilized in breeding programs (www.icrisat.org). This highlights low utilization of genetic resources by breeders. According to Foyer et al. (2016), the low utilization of genetic resources has led to stagnation of grain legume yields. In order to increase adoption of grain legumes, improved varieties that are drought- and heat-stress tolerant, nutrient dense and high yielding should be made available. This is still in its infancy and there is need for novel biotechnological techniques such as marker-assisted selection to speed up grain legume improvement. This should include whole-genome sequencing in the existing legume accessions including crop wild relatives to develop new molecular markers.

3.4.1.1 Seed Systems

In semi-arid and arid tropics, 80%–90% of grain legume seed systems are farmer-driven (farmer seed systems). This means that farmers use farm-saved seed from the previous harvest, acquire them from other farmers through barter or gifts or obtain them from informal local markets (Almekinders et al., 1994; Almekinders and Louwaars, 2002; Bèye and Wopereis, 2014; Coomes et al., 2015; Jones et al., 2001; Reddy et al., 2010; USAID, 2012; Wekundah, 2012). This seed is often in the form of landraces, which are open-pollinated varieties that are often the product of many years (>100 years) of natural and farmer selection (Zeven, 1998). In some instances, seed companies supply landraces of both major and minor grain legumes that are not certified or tested (Almekinders and Louwaars, 2002; Reddy et al., 2010; Wekundah, 2012). They take advantage of their strategic positioning in the agriculture sector to source seed of grain legumes and supply them to research institutions or farmers. Farmers have also been reported to purchase hybrid seed, which is the product (first-generation progeny) of a cross between two unrelated (genetic dissimilar) parents (Mathews and Saxena, 2005), and then recycle it similarly to how they recycle landraces (Reddy et al., 2010; Wekundah, 2012). However, unlike for landraces and other open-pollinated varieties, recycling hybrid seeds has negative implications on subsequent seed quality. In addition, most grain legumes that are grown in the semi-arid and arid tropics are self-pollinating plants, hence recycling seeds may result in loss of vigour, decrease in immunity to diseases and reduced adaptability to changing environments (Wekundah, 2012).

Adoption of improved seed will significantly increase productivity if it is accompanied by the adoption of best management practices. Promoting hybrid seed may also come with increased dependency on other agricultural inputs such as chemicals, fertilizers and water (Bezner Kerr, 2013; Kerr, 2012). This may create new challenges under low input agriculture systems that typify the semi-arid and arid tropics, as farmers may not be able to afford the use of external inputs. In this regard, the use of improved open-pollinated varieties adapted to a range of environments would be more desirable. Thus, promoting grain legumes in cropping systems will require formulation of dynamic strategies that ensure availability and farmers' adoption of improved seed as well as adoption of best management practices that allow for yield maximization. This should be underpinned by viable and sustainable seed systems (formal and informal) that are beneficial to all role players (breeders, government and farmers).

Formal seed systems are discouraged by farmers' tendency to recycle seed, thereby decreasing the demand for certified seed (Muigai et al. undated). However, farmers' tendency to recycle seeds is influenced by several factors such as high cost of purchasing hybrid seed every season and lack of formal seed suppliers in rural areas. In addition, use of hybrids also risks loss of benefits such as ease of exchanging or sharing seed as well as earning income from selling seeds on the informal market. This highlights the need to integrate formal and informal seed systems when promoting grain legumes. Muigai et al. (undated) suggested integrating informal seed channels into formal seed structures by providing foundation seed to selected rural farmer groups to multiply. This should be supported by extension advice on seed production, processing, treatment, storage and developing a legal framework that permits marketing of certified and uncertified seed of acceptable genetic purity and germination quality. This will provide resource-poor farmers with quality seeds of improved varieties at affordable prices. A similar strategy is underway in Nigeria aimed to "sustainably improve farmers' access to high quality and affordable cassava planting material through the development and promotion of models for seed provisions" (www.iita.org). Such models, if successful, could be adopted and restructured for grain legumes.

3.4.2 Production

3.4.2.1. Agronomy

Soil fertility is one of the major constraints in subsistence agriculture. Studies have shown that including grain legumes in cropping systems improves soil fertility (Karpenstein-Machan and Stuelpnagel, 2000; Reckling et al., 2015; Smith et al., 2016). This could be through relay cropping, intercropping, crop rotations or double cropping (Karpenstein-Machan and Stuelpnagel, 2000; Reckling et al., 2015; Smith et al., 2016). Legumes have also been successfully used as cover crops to improve soil fertility, control pests and suppress weeds (Blevins et al., 1990; Chabi-Olaye et al., 2005; Rühlemann and Schmidtke, 2015). While the role of grain legumes in increasing soil nitrogen cannot be denied, other macro- and micro-nutrients cannot be ignored. A deficiency of other nutrients such as phosphorous, boron and molybdenum may hinder nitrogen fixation (Divito and Sadras, 2014; Sur et al., 2010; Zahran, 1999). In addition, subsistence farmers often do not use inoculants to stimulate the formation of nitrogen-fixing nodules. Studies on dry bean, groundnut, soybean and cowpea have shown that under marginal soils inoculating seed with Rhizobia improves nitrogen-fixation capacity and yield (Cheruiyot et al., 2013; Mweetwa et al., 2014). There should always be a balance of the essential soil nutrients that are required for growth and reproduction of grain legumes to get the maximum yield. Rural farmers should have access to soil analyses. This will aid in correcting soil fertility to maximize yield. While use of fertilizer may be limited due to affordability, options such as manure, compost and crop residues could be explored.

Another major agronomic component of grain legumes is weeding. According to Avola et al. (Avola et al., 2008), grain legumes are poor competitors with weeds. Without proper weed control, weeds can cause significant yield losses (Olorunmaiye, 2010; Rubiales and Fernández-Aparicio, 2011). Groundnut, soybean and bambara groundnut have been observed to be among the poorest competitors with weeds and require constant weeding compared to other legumes such as cowpea and pigeon pea (Abdelhamid and El-Metwally, 2008; Bhale et al., 2012; Martin et al., 2009; Mhango et al., 2013). A study in Malawi showed that one of the factors influencing farmers' adoption of grain legumes in cropping systems was the high labour required due to constant weeding (Mhango et al., 2013). There is need for sustainable weed control strategies for poor rural farmers to increase adoption of grain legumes. This should include low-cost mechanical weeding machines and agronomic practices to reduce weed infestation. The latter includes research on the effects of mulching, spatial arrangements and critical periods for weed control in different grain legume species.

The adverse environmental conditions that typify most of the semi-arid and arid tropics suggest that currently grain legumes are being grown under sub-optimal conditions. This could explain the high incidences of aflatoxins reported in legumes, especially groundnut. Aflatoxins are a group of chemically similar toxic fungal metabolites (mycotoxins) produced by certain moulds of the genus *Aspergillus* growing on several raw food commodities (Luchese and Harrigan, 1993). Aflatoxins, notably *Aspergillus flavus*, are naturally abundant and often found when certain grain legumes are grown under stressful conditions such as drought (Heathcote and Hibbert, 1978). Aflatoxin levels are high in groundnut (up to 11,865 μg/kg) (Chala et al., 2013). This has become a concern for the production and export of groundnuts in semi-arid and arid tropics (www.tradeforum.org). This is disconcerting; for the period 2000–2006, ≈80% of SSA's groundnut exports to the European Union were non-compliant with the Codex standard of aflatoxin levels (>50 ppb) (Diaz Rios, 2008). Loss of markets therefore becomes a disincentive for farmers to continue production. Improved agronomic practices could lower the incidence of aflatoxins.

With the exception of major grain legumes, there is a lack of robust empirical information describing the agronomy of most grain legumes suitable for cultivation in the semi-arid and arid tropics. While this information may be available in few national agricultural research stations, it remains inaccessible to farmers. Rural farmers who still cultivate minor grain legumes mostly rely on indigenous knowledge and continue to get low yields, further marginalizing the continued production of minor grain legumes.

3.4.2.2 Water Use and Water Use Efficiency

In semi-arid and arid tropics, where water is the most limiting input to crop production, crop water requirement is an important factor. Crops that use less water are becoming increasingly important as one of the strategies to increase food production under conditions of water scarcity. Research on water use of grain legumes showed that cowpea and fababean had low water use ranging between 78 and 258 mm and 101 and 261 mm, respectively (Table 3.4). Lentils could also be considered low water users, especially when compared to major grain legumes such as dry bean, groundnut and soybean that had water use ranging from 318 to 463 mm, 697 to 809 mm and 598 to 690 mm, respectively (Table 3.4). The high water requirement of groundnuts could also explain the high incidence of aflatoxins, as they are more prone to water-deficit stress. It could thus be inferred that cowpea, fababean, lentil, chickpea and common pea are suitable for growing in arid and semi-arid conditions where seasonal rainfall is low (200 to 400 mm) (Table 3.4).

However, low water use does not necessarily imply high water use efficiency (WUE). Water use efficiency of legumes ranges from 1.7 to 15.9 kg·ha^{-1}·mm^{-1} with various species showing noticeable differences in WUE (Table 3.4). These values are low when compared to WUE values reported for cereal and root and tuber crops. For maize and sorghum, the lowest reported WUE value was 4 kg·ha^{-1}·mm^{-1} (Igbadun et al., 2006) while the highest was up to 85 kg·ha^{-1}·mm^{-1} (Saeed and El-Nadi, 1998; Tijani et al., 2008). Potatoes on the other hand have WUE values as high as 195 kg·ha^{-1}·mm^{-1} (Badr et al., 2012). It cannot be disputed that cereals and root and tuber crops are more water use efficient when compared to grain legumes. Values of water use and WUE are, however, wide-ranging and lack robustness as they were determined under different management and environmental conditions and are thus not conservative (van Halsema and Vincent, 2012). Water productivity (WP), which is the net benefits accrued per unit water consumed (Molden et al., 2003), offers greater spatial and temporal stability and is a true efficacy parameter of the crop production process (van Halsema and Vincent, 2012).

Table 3.4: Water use and water use efficiency (WUE) of selected grain legumes.

Species	Water Use	Yield	WUE	Climate	Source
	mm	kg·ha^{-1}	kg dry matter ha^{-1} mm^{-1}		
Dry bean	318–463	1407–4031	1.7–10.9	Mediterranean	(Muñoz-Perea et al., 2007)
Groundnut	697–809	2080–4240	3.96–5.25	Semi-arid	(Patel et al., 2008)
Chickpea	150–340	358–1357	1.9–3.6	Mediterranean	(Zhang et al., 2000)
Soybean	598–690	710–1910	1.16–2.80	Semi-arid	(Obalum et al., 2011)
Cowpea	78–258	1020–1340	0.11–0.2	Semi-arid	(Abayomi et al., 2008)
Bambara groundnut	300–638	500–2400	0.1–0.12	Semi-arid	(Mabhaudhi et al., 2013)
Pigeon pea	331–551	1816–2643	3.38–6.97	Semi-arid	(Vimalendran and Latha, 2014)
Common pea	177–266	1040–2240	6–15.9	Mediterranean	(Siddique et al., 2001)
Fababean	101–261	420–1920	1.7–12.5	Mediterranean	(Siddique et al., 2001)
Lentil	160–308	339–1657	2.3–4.5	Mediterranean	(Zhang et al., 2000)
White lupine	178–272	1570	2.1–8.5	Mediterranean	(Siddique et al., 2001)

NB. Data were obtained from experiments conducted under varying environmental and management conditions.

3.4.3 Post-Harvest Handling, Storage and Value Addition

After harvesting, products go through some sort of transformation from their original state to a more valuable state. This is referred to as value addition. Value addition can be viewed as the benefits obtained from a product with respect to quality, form and functionality (Anderson and Hanselka, 2009). This includes the transformation of food to nutrients that are utilized by the body (Boland, 2009). Value addition also includes agro-processing which describes the manufacturing processes involved to derive products from agricultural raw products (FAO, 1997).

3.4.3.1 Post-Harvest Handling and Storage

Subsistence farmers still harvest grain legumes manually. This can lead to splitting and significant yield losses (≈20%) (Williams, 1994). In many parts of India, low-cost mechanical harvesting equipment has been designed for groundnut and dry bean to minimize labour and grain losses during harvesting (Mothander et al., 1989). There is also a need for similar low-cost technologies for other grain legumes coupled with suitable and appropriate maturity and harvest indices to aid farmers in correctly determining time of harvest; this will minimize grain losses during harvesting.

One of the major advantages of grain legumes is their long shelf life hence availability throughout the year. However, this is largely determined by storage conditions. Once the grain legumes have been threshed, the seeds must be stored at ≈12% moisture content and temperatures below 15 °C to avoid discoloration, mould and fungi. Some grain legumes are very sensitive during storage and, if care is not taken, up to 50% of storage losses can be incurred (Kat et al., 1992). For example, when chickpea seed is harvested, its outside seed coat usually has a lower moisture level than the inside of the seed. If left to sit in storage, the moisture level can balance out (tempering/sweating), causing the overall moisture level to rise. In this way, chickpeas that are harvested at a safe moisture level can, after a week, exceed the recommended 14%. Left untreated, the harvest can spoil. For this reason, chickpea producers often store the crop in a hopper-bottomed bin that has aeration, which can help bring down the moisture level (www.pea-lentil.com). This information may not be available to subsistence farmers and they may not have access to specialized storage containers. This is one of the reasons why there is a shift towards promoting value chain research; if chickpeas are promoted to farmers, this must be accompanied by knowledge of chickpea post-harvest handling and storage as well as provision of specialized storage containers to avoid detrimental post-harvest losses.

Under proper storage conditions, grain legumes can be stored for up to three years (Summerfield, 2012). Considering the predicted increase in drought occurrences, this is an important attribute as stored grain can be consumed during drought and when there is a shortage of food. However, weevils, rats, bruchids and other storage pests can be a problem in storage and proper chemicals need to be used to control them (Summerfield, 2012). Poor storage environment can result in colour loss, moisture absorption, and desorption as well as hardness or case hardness issues (McCormack, 2004). In semi-arid and arid tropics, subsistence farmers frequently experience such storage challenges and this could be partly why they are discouraged from producing large quantities. If there are no markets to sell the surplus grain to, this acts as a further disincentive to farmers and they subsequently only produce grain they can consume in the short term. Poor storage conditions may also influence the seed quality (viability and vigour) reserved for the next season. While grain legumes may have a longer shelf life compared to vegetables, dairy products, fruits, and meat products, currently this advantage has not been fully explored due to farmers' lack of appropriate storage conditions. This ultimately compromises the potential of grain legume availability all year round.

3.4.3.2 Nutritional Quality

Grain legumes contain 5% to 39% protein with white lupine and soybean being the highest protein sources (Table 3.5) (Messina, 1999; Večerek et al., 2008). By comparison, vegetables and cereals contain 2% and 8% to 12% protein, respectively (www.pea-lentil.com). This makes grain legumes the best source of proteins among all the food crops. In the absence of meat, grain legumes offer the best protein supplement to meet the recommended daily allowance (RDA) of 56 g (Table 3.5). Soybean contains the most protein compared to other grain legumes; this could explain why it has been widely accepted. In addition to being good sources of protein, some grain legumes such as bambara groundnut, soybean and cowpea contain reasonable amounts of carbohydrates (up to 56%) (Table 3.5). Soybean and tepary bean contain sufficient iron to meet the RDA for an adult male and almost enough to meet the RDA of an adult female (Table 3.5). This implies that incorporating these crops in diets could alleviate the high prevalence of anaemia in semi-arid and arid tropics. Soybean, dry beans, bambara groundnut and tepary bean contain >160 mg of calcium which is higher than the same serving of milk (125 mg per 100 g milk) (Table 3.5) (Smith et al., 1985).

Cereals are the major source of carbohydrates but are poor sources of proteins and micronutrients providing ≈12 g protein, 10 to 140 mg calcium, 0.5 to 3.9 mg iron, and 0.6 to 3.3 mg zinc per 100 g serving (McKevith, 2004). This is comparatively lower than grain legumes and justifies the need to promote grain legumes to compliment cereals in diets.

However, these values are for raw seeds and it will be impetuous to not consider how the different processes affect nutritional value that the grain legumes go through before they are consumed. The presence of anti-nutritional factors (ANFs) and aflatoxins should also be considered as they pose an impediment to utilization of grain legumes.

3.4.3.2.1 Anti-Nutrient Factors

Anti-nutrient factors (ANFs) are chemical compounds synthesized by plants for their own defence. Metabolically, synthesis of anti-nutrients is a favourable attribute as it is an adaptive mechanism. However, synthesis of anti-nutrients is through inactivation of some nutrients that are important to humans (Gemede and Ratta, 2014). This ultimately decreases nutritive value of foods. Common ANFs in legumes include tannins, phytates, oxalates, saponins, lectins, alkaloids, protease inhibitors cynogenic glucosides and oligosaccharides. They occur in small quantities ranging from 0.2% to 4%. Some ANFs cause undesirable effects to humans when consumed in excess (Gilani et al., 2012). Phytic acid impairs the absorption of iron, zinc and calcium. Lectins are difficult to digest and may affect the cells lining the intestinal tract. Saponins increase intestinal permeability also known as leaky gut (Messina, 1999). Oligosaccharides occur in large quantities (≈20–50 mg/g) and are responsible for the flatulence associated with consuming legumes (Messina, 1999). However, ANFs are not all undesirable; they have some benefits. For example, phytates and saponins are believed to lower the risk of colon and breast cancer (Bennink, 2002). Despite the latter, generally anti-nutrients are not desirable. Minimizing ANFs in grain legumes is linked to improving agronomic practices and minimizing stress during production.

Table 3.5: Average nutrient content of selected grain legumes per 100 g raw mature seeds.

Species	Energy	Protein	Carbohydrates	Fat	Vit A	Iron	Zinc	Calcium	Source
	Kcal		g		µg		mg		
*RDA		56.0; 46.0	130.0	20.0–35.0	900.0; 700.0	8.0; 18.0	11; 8	1000.0	(Joint and Organization, 2005)
Dry bean	333.0	21.8	2.5	2.5	–	4.7	–	183.0	(Geil and Anderson, 1994)
Groundnut	570.0	25.0	21.0	48.0	–	2.0	3.3	62.0	(Atasie et al., 2009)
Chickpea	164.0	8.9	27.0	2.6	1.0	2.89	1.5	49.0	(Iqbal et al., 2006)
Soybean	446.0	36.5	30.2	19.9	1.0	15.7	4.9	277.0	(Liu, 1997)
Lablab	50.0	2.9	9.2	0.3	–	0.76	0.4	41.0	(Deka and Sarkar, 1990)
Cowpea	116.0	7.8	20.8	0.5	–	2.51	1.3	24.0	
Bambara groundnut	367.0	20.6	56.0	6.6	–	5.96	7.9	219.0	(Yao et al., 2015)
Pigeon pea	136.0	7.2	28.9	1.6	–	1.6	1.0	42.0	(Singh et al., 1984)
Tepary bean	–	–	–	–	–	12.6	5.0	165.0	(Sheerens et al., 1983)
Common pea	81.0	5.4	14.0	0.4	38.0	1.47	1.2	25.0	
Fababean	341.0	8.0	18.0	0.7	–	6.7	3.1	103.0	(Crépon et al., 2010)
Lentil	353.0	26.0	60.0	1.0	–	7.54	4.8	56.0	
White lupine	1741.0	39	11.5	5.8	–	3.1	4.5	0.68	(Večerek et al., 2008)

*RDA = Recommended Dietary Allowance (Male; Female); Nutritional values may vary from one variety to the other.

3.4.3.3 Processing and Utilization

In rural communities, the processing and utilization of grain legumes has a long history that is intimately linked to women and their traditional livelihood tasks (Ezumah and Di Domenico, 1995; Modi et al., 2006). This will be an advantage for promoting grain legumes for improved household nutrition in semi-arid and arid tropics where women have greater influence over household food choices, child nutrition and ultimately health (FAO, 2015). Grain legumes can play an increasingly important role as a source of income in rural communities, especially those near towns and cities. The money could be used towards other household needs and children's education (FAO, 2015).

Depending on the type of grain legume and the intended use, the various processes may differ. One of the initial steps (primary processes) is to further dry the harvested pods. Drying is done under the sun and, depending on resources; grains are spread on the ground or on a raised platform. After sun drying comes two processes that are considered time consuming and laborious when done manually. This includes (i) dehusking, which is the process of removing the husks; and (ii) winnowing which involves separating the husks from the seed (Subuola et al., 2012). Resource-poor farmers use manual methods (mortar with pestles and wooden or stone shellers). These processes require manual labour and this could also partly explain the low cultivated areas for grain legumes in rural households. Labour is limited due to rural to urban migration of the economically active age group (Haan, 1997). In this regard, the development of low-cost technologies for processing the harvest could go some way in encouraging farmers to allocate more land to grain legumes.

Secondary processes include, but are not limited to, soaking, cooking, fermenting and germinating (Subuola et al., 2012). Cooking improves appeal, nutrition and digestibility of grain legumes. In several grain legumes, cooking time (boiling) of pods and/or grains is comparatively lengthy (three to five hours). This could be a disincentive in rural areas where fuelwood and water for cooking are scarce (Deshpande, 2000). Soaking and cooking time of grain legumes have also been shown to affect nutritional quality of some grain legumes (Güzel and Sayar, 2012). It was observed that proteins, minerals and carbohydrate content in seeds decreased by 16% to 20%, 30% and 18% to 40%, respectively, following cooking (Mahadevamma and Tharanathan, 2004; Meiners et al., 1976; Siddhuraju et al., 2000). This raises the challenge of developing appropriate cooking methods that maximize nutrient retention. Although the challenges related to cooking time and nutrient retention have been raised, research still lags in providing solutions. Such solutions could be useful in unlocking their value.

While legumes have mainly been considered for their grains, young tender leaves and flowers of some grain legumes can also be consumed as vegetables (Manay and Swamy, 2001; Toensmeier, 2007). Leaves and flowers are rich in vitamins and minerals (Manay and Swamy, 2001; Toensmeier, 2007). Tapping into this potential could contribute to dietary diversity through unlocking a useful source of vitamins and minerals. This could be explored when other leafy vegetables are not available as well as to increase the leafy vegetable basket. However, there are scant studies reporting on the nutritional status of young tender leaves and flowers of legumes as well as harvest times.

3.4.3.3.1 Animal Feed

In addition to human consumption, grain legumes can be used for fodder. The value of grain legumes in livestock production has been explored for forage legumes such as *Medicago sativa* (alfafa), clover (*Trifolium spp*.) and vetch (*Vicia sativa*). This is mainly targeted for commercial livestock production and is unaffordable for subsistence farmers. Subsistence farmers can utilize grain legume residues for fodder but this remains underutilised and poorly documented in the semi-arid and arid tropics (Sumberg, 2002). After harvesting pods, leaves of grain legumes such as chickpea, lentil, cowpea, common pea, soybean, fababean and lablab can be left in the field for animal grazing. Grain, leaves and husks of soybean, common pea, fababean, lupine, cowpea, bambara groundnut, velvet bean, chickpea, lentils and lablab can be ground and used as animal feed (Crépon et al., 2010; Dixon and Hosking, 1992; Huisman and Van der Poel, 1994; Jezierny et al., 2010). They form an important plant-based protein source that can be fed directly or mixed with cereals to form complete meals (Nji et al., 2004; Siddhuraju et al., 2000). The fact that most grain legumes have a dual purpose (i.e., human and animal feed) makes them ideal for inclusion in crop–livestock systems that characterize smallholder and subsistence agriculture.

3.4.3.3.2 Agro-Processing

Agro-processing enables conversion of farm produce to various commodities that can attract different markets. Agro-processing increases shelf life, reduces wastage and has the potential to increase income of subsistence farmers (Food and Agriculture Organization, 1997). Due to rising incomes and change in lifestyles, the demand for processed foods is increasing, creating opportunities for the agro-processing industry (International Monetary Fund, 2014; Timmer, 1995).

Agro-processing in various countries has been biased towards cereals, fruits, vegetables, oil, textiles and beverages. In semi-arid and arid tropics, the major grain legumes dominate grain legume agro-processing. Dry beans are commonly tinned or sold raw with proper packaging and branding. Groundnuts are commonly sold roasted with proper packaging and branding or are processed into peanut butter. Soybean is the most versatile among all the grain legumes and can be processed to milk, curd, sauce, cheese and chunks. These products are common amongst vegetarians and those who are allergic to cow milk. In addition to the above products, groundnuts and soybean are processed to produce oil. The multiple uses make soybean and groundnut the most economically important grain legumes.

On the contrary, minor grain legumes have received less attention in terms of agro-processing. This inadvertently reduces their utilization and subsequent demand; this may explain why seed companies tend to not focus on them. Despite the lack of research, several minor grain legumes have potential for processing into various products. For example, bambara groundnut seed can be used to produce vegetable milk although this potential is currently underexplored (Agunbiade et al., 2011; Brough et al., 1993). India has made a significant milestone on agro-processing of minor grain legumes (chickpeas and lentils). Promoting agro-processing of minor grain legumes could open new value chains and opportunities for rural farmers to participate in these value chains. Agro-processing would also increase demand for minor grain legumes thus necessitating increased production and availability of seed. Increasing opportunities for rural farmers to earn incomes and exit poverty is key to sustainable development in the semi-arid and arid tropics.

In Thailand, agro-processing reduced poverty in rural areas through (i) the purchase of agricultural products by the agro-processing industry; and (ii) establishing agro-processing industries near rural areas in-order to employ poor farmers (Watanabe et al., 2009). This provides a successful case study for governments in developing countries to establish grain legume agro-processing facilities for rural farmers. India, in its efforts to encourage grain legume production, made available more than 10,000 smallholder grain legume mills (Chengappa, 2004). Though this is incomparable to cereal hullers and mills (>200,000), it served as a starting point (Chengappa, 2004). Developing countries should embark on similar projects to facilitate agro-processing in rural areas and make grain legume products more available at low cost. To realize this, research, development and innovation should support the development of acceptable standards, branding and marketing. Promotion of agro-processing could create business opportunities for rural farmers (Singh et al., 2007).

3.4.4 Marketing

Ultimately, within the value chain, there must be a market to consume the grain legume products. Marketing structures are divided into three levels—(i) the traditional/local market; (ii) wholesaler/processor market; and (iii) the retailer market. For grain legumes in the rural areas of semi-arid and arid tropics, the traditional market is the dominant market level. Major grain legumes are available on both the traditional and retail market while minor grain legumes are only found on the traditional market (Giller et al., 2011). On the traditional market, grain legumes are sold whole with minimum value addition. As a result, they do not fetch a high price and products move slowly due to limited utilization. This discourages farmers from producing surplus grain legumes hence resorting to growing cereals. Cereals have a higher demand on all market levels hence they sell fast. This makes it attractive for subsistence farmers as they are guaranteed to sell their product.

Cereals have also enjoyed much innovation concerning their agro-processing. There is a wide variety of cereal products thus attracting a wider market and ultimately increasing utilization. The number of grain legume products are only one-third of the number of cereal products (Kachru, 2010). This is further evidence that cereals are more utilized than grain legumes. To increase grain legume utilization, the same strategy of product diversification could be employed. This will broaden the grain legume market and ultimately increase utilization. However, product diversification is highly dependent on agro-processing. Currently, agro-processing has only focused on a few major grain legumes. Effective product diversification will require inclusion of minor grain legumes. Minor grain legumes are currently being manually processed by farmers in rural areas implying that there is scope for agro-processing in these grain legumes. There is need for investments in research, development and innovation to establish successful and sustainable large- and smallholder grain legume agro-processing facilities. However, such development should pay attention not to exclude rural farmers.

Rural farmers are the primary producers of grain legumes. The majority of them continue to live in poverty and are the most vulnerable to food and nutrition insecurity (FAO, 2015). The current marketing and distribution channels for value-added grain legumes have not benefitted rural farmers. Value added products are expensive in retail stores and the traditional market offers limited utilization. Thus, promotion of grain legume agro-processing as a strategy to market grain legumes should include rural farmers, as they are the main target of strategies to alleviate food and nutrition security. This will benefit rural farmers through (i) product diversification, which will ultimately increase utilization and subsequently improve protein intake in households; and (ii) provide value added products that will attract a wider market and that will sell faster, thereby translating to increased household income.

3.4.5 Grain Legumes: Opportunities and Constraints

The grain legume research value chain has largely focused on grain legumes of regional economic importance. With approximately 30 grain legume species being grown in the semi-arid and arid tropics, only less than 50% of these have received significant research attention. This is mainly because research funding has favoured a few major grain legumes (chickpea, dry bean, cowpea, fababean, groundnut, lentil, pigeon pea and soybean). These grain legumes are also part of the CGIAR's mandate crops; hence, they have received significant research attention compared to other minor grain legumes (Gepts et al., 2005; ICRISAT et al., 2012). There is an opportunity to increase the grain legume basket by tapping into the potential of other minor grain legumes. Thus far, there is scant documented information on these crops due to lack of funding to support research, development and innovation on these crops.

Breeding and crop improvement of grain legumes has been limited by the poor demand of seed. In semi-arid and arid tropics, farmers continue to recycle their own seed. Failure by breeders to improve farmers' varieties and tap into certain beneficial traits has confined the production of minor grain legumes to the ecological niches where they have been conserved. The semi-arid and arid tropics are rich in grain legume biodiversity, which is currently underutilised. With increased promotion of grain legumes, there is an opportunity to exploit these genetic resources. This could result in development of high-yielding cultivars that are suitable for growing in water scarce environments. The reported low yields of grain legumes have made them unattractive for farming. The low yields could also be because of lack of improved cultivars and farmers' agronomic knowledge, which is mostly based on indigenous knowledge.

Soil fertility is one of the major challenges in rural cropping systems (Sanchez, 2002). Grain legumes fix nitrogen, a unique feature that makes them important under marginal conditions. While nitrogen fixation is a key point for the promotion of grain legumes, there is poor understanding that nitrogen fixation is influenced by other factors such as presence of nitrogen fixing bacteria, lack of other soil nutrients and abiotic stresses (Carranca et al., 1999; Zahran, 1999). In addition, as previously alluded to, nitrogen fixation is often limited by the lack of inoculants in rural cropping systems. Water is the most limiting resource in agriculture; this has led to crop failures, poor yields, and high levels of aflatoxins and ANFs in major grain legumes. Several minor grain legumes are more drought tolerant and water use efficient than major grain legumes and offer opportunities for cultivation in dry areas where water is most limited. This would imply that their ability to fix nitrogen would be less sensitive to water stress as well; however, there is a need to test such a hypothesis. In this regard, they also offer opportunities for addressing food and nutrition insecurity in marginal agricultural production areas where most major crops may fail.

Grain legumes are nutritious and have the potential to improve nutritional status of the rural poor. However, most published nutrition values are derived from raw seeds. There is need for research that assesses the nutritional profile of grain legumes after processing, as this would be more informative to dietary intake. Most grain legumes are characterized by long cooking time and are processed differently by cultures of semi-arid and arid tropics. Long cooking time often creates challenges as it means more water and energy are required to prepare them—resources that are equally scarce in rural areas. This suggests that there are opportunities for breeders, agronomists and nutritionists to work together to unlock such challenges. This would lead to improved utilization of grain legumes.

Owing to their long shelf life, legumes are available throughout the year thus offering a more sustainable protein source for poor rural farmers. However, even with this characteristic, given the reported challenges with post-harvest handling and storage, grain legumes are not reaching their potential shelf life. There are opportunities for agricultural engineers to develop low-cost post-harvest technologies for use in rural areas. Improving storage could serve as incentive for farmers to produce more of a crop as they know they can store it for longer periods.

The market for grain legumes, in particular minor grain legumes, remains underdeveloped. This confines their utilization to the niche areas in which they are produced. Consequently, grain legumes have become a poor and slow income-generating source for rural farmers, acting as a disincentive to their continued production despite the benefits associated with them. Opportunities that exist in agro-processing could lead to the opening of new markets through value addition and product diversification. Improved income realized from agro-processing could promote autonomous pathways out of poverty for poor rural households.

3.5 Recommendations

There is a large diversity of grain legumes that fit into various agro-ecologies. This implies that grain legumes can be grown in various environments. Focusing on a few specific grain legumes leaves farmers with limited choices and forces farmers to grow them in unsuitable environments and risk crop failure. If grain legumes are to be promoted to increase dietary diversity, then there is need to broaden the grain legume basket by increasing research, development and innovation on other minor grain legumes. While regionally important grain legumes have received breeding attention compared to other minor grain legumes, there is still need for pre-breeding to develop new gene pools for all grain legumes. This will be followed by breeding and commercialization of cultivars that are nutrient dense and well-adapted to semi-arid and arid conditions. Breeding efforts and subsequent commercialization of minor grain legumes should recognize the role played by farmers in rural areas and create opportunities for meaningful access and beneficiation.

There should be more integration of indigenous and scientific knowledge to allow rural farmers to improve grain yield and quality. It has been realized that soil fertility is a constraint in rural cropping systems and that grain legumes could improve soil fertility. To improve soil fertility, legumes should be incorporated into cropping systems through relay cropping, intercropping, crop rotations or double cropping. Researchers need to make practical recommendations based on water use and water productivity of grain legumes and focus on improving crop water productivity. This should include minor grain legumes that are indigenous to semi-arid and arid conditions, as they have been observed to be more drought tolerant when compared to major grain legumes.

3.6 Conclusions

There is a high prevalence of food and nutrition insecurity in semi-arid and arid tropics. Measures to increase food production should create a balance between increasing productivity, water scarcity and nutrition. The fact that grain legumes are rich sources of proteins and micronutrients suggests that they have a role to play in contributing to food and nutrition security in poor rural communities. Use of grain legumes for both human and animal consumption provides an opportunity to improve sustainability of crop-livestock systems in the semi-arid and arid tropics. The large diversity of grain legumes makes them adaptable to a range of environments, especially marginal agriculture production areas. However, a poorly developed and understood value chain currently limits the realization of this potential. Aspects of their breeding, seed systems, production, marketing and utilization are not well explained. This is mostly the case for minor legumes, which incidentally hold the most potential for improving food and nutrition security in semi-arid and arid areas. Focusing on the value chain could aid researchers to identify and unlock barriers for the promotion of legumes in semi-arid and arid tropics. Despite the large diversity of grain legumes, research has been biased towards major grain legumes. Ironically, the minor grain legumes are the ones indigenous to semi-arid and arid tropics and hence are more adaptable to water-scarce conditions. There is need to increase the legume basket by adding minor grain legumes. This will also act as a buffer when major grain legumes are not successful due to drought.

References

Abate, T., Alene, A.D., Bergvinson, D., Shiferaw, B., Silim, S., Orr, A., Asfaw, S., 2012. Tropical grain legumes in Africa and south Asia: knowledge and opportunities. International Crops Research Institute for the Semi-aridArid Tropics.

Abayomi, Y.A., Ajibade, T. V, Sammuel, O.F., Saadudeen, B.F., 2008. Growth and yield responses of cowpea (*Vigna unguiculata* (L.) Walp) genotypes to nitrogen fertilizer (NPK) application in the Southern Guinea Savanna zone of Nigeria. Asian J. Plant Sci 7, 170–176.

Abberton, M., 2010. Enhancing the role of legumes: potential and obstacles. Grassl. Carbon sequestration Manag. Policy Econ. 11, 177.

Abdelhamid, M.T., El-Metwally, I.M., 2008. Growth, nodulation, and yield of soybean and associated weeds as affected by weed management. Planta Daninha 26, 855–863.

Agunbiade, S.O., Amosu, A.M., Degun, A.M., Omeonu, P.E., 2011. The physio-chemical and organoleptic properties of milk fabricated from Glycine max, Vigna subterranean and Sphenostylis stenocarpa. J. Chem. Pharm. Res 3, 918–924.

Akinyele, I.O., Shokunbi, O.S., 2015. Concentrations of Mn, Fe, Cu, Zn, Cr, Cd, Pb, Ni in selected Nigerian tubers, legumes and cereals and estimates of the adult daily intakes. Food Chem. 173, 702–8. doi:10.1016/j.foodchem.2014.10.098

Allen, O.N., Allen, E.K., 1981. The Leguminosae. A source book of characteristics, uses and nodulation. Legum. A source B. Charact. Uses nodulation.

Alleyne, G.A.O., Hay, R.W., Picou, D.I., Stanfield, J.P., Whitehead, R.G., 1977. Protein-energy malnutrition.

Alliance for a Green Revolution in Africa (AGRA), 2013. Africa Agriculture Status Report: Focus on staple crops. Nairobi Kenya. doi:10.1007/s13398-014-0173-7.2

Almekinders, C.J.M., Louwaars, N.P., 2002. The Importance of the Farmers â€TM Seed Systems in a Functional National Seed Sector. J. New Seeds 4:1-2, 15–33. doi:10.1300/J153v04n01

Almekinders, C.J.M., Louwaars, N.P., de Bruijn, G.H., 1994. Local seed systems and their importance for an improved seed supply in developing countries. Euphytica 78, 207–216. doi:10.1007/BF00027519

Anderson, D.P., Hanselka, D., 2009. Adding value to agricultural products. Texas FARMER Collect.

Atasie, V.N., Akinhanmi, T.F., Ojiodu, C.C., 2009. Proximate analysis and physico-chemical properties of groundnut (*Arachis hypogaea* L.). Pakistan J. Nutr. 8, 194–197.

Avola, G., Cavallaro, V., Patanè, C., Riggi, E., 2008. Gas exchange and photosynthetic water use efficiency in response to light, CO 2 concentration and temperature in *Vicia faba*. J. Plant Physiol. 165, 796–804.

Badr, M.A., El-Tohamy, W.A., Zaghloul, A.M., 2012. Yield and water use efficiency of potato grown under different irrigation and nitrogen levels in an arid region. Agric. Water Manag. 110, 9–15.

Bennink, M.R., 2002. Consumption of black beans and navy beans (*Phaseolus vulgaris*) reduced azoxymethane-induced colon cancer in rats. Nutr. Cancer 44, 60–65.

Bèye, A.M., Wopereis, M.C.S., 2014. Cultivating knowledge on seed systems and seed strategies: case of the rice crop. Net J. Agric. Sci. 2, 11–29.

Bezner Kerr, R., 2013. Seed struggles and food sovereignty in northern Malawi. J. Peasant Stud. 40, 867–897.

Bhale, V.M., Karmore, J. V, Patil, Y.R., Krishi, P.D., 2012. Integrated weed management in groundnut (*Arachis hypogea*). Pakistan J. Weed Sci. Res. 18, 733–739.

Blevins, R.L., Herbek, J.H., Frye, W.W., 1990. Legume cover crops as a nitrogen source for no-till corn and grain sorghum. Agron. J. 82, 769–772.

Boland, M.A., 2009. Leadership Development in Agricultural Economics: Challenges for Academic Units. J. Agric. Resour. Econ. 367–382.

Boschin, G., Arnoldi, A., 2011. Legumes are valuable sources of tocopherols. Food Chem. 127, 1199–1203.

Boswell, V.G., 1926. The influence of temperature upon the growth and yield of garden peas, in: Proc. Amer. Soc. Hort. Sci. pp. 162–168.

Brough, S.H., Azam-Ali, S.N., Taylor, A.J., 1993. The potential of bambara groundnut (*Vigna subterranea*) in vegetable milk production and basic protein functionality systems. Food Chem. 47, 277–283.

Carranca, C., De Varennes, A., Rolston, D., 1999. Biological nitrogen fixation by fababean, pea and chickpea, under field conditions, estimated by the 15N isotope dilution technique. Eur. J. Agron. 10, 49–56.

Chabi-Olaye, A., Nolte, C., Schulthess, F., Borgemeister, C., 2005. Effects of grain legumes and cover crops on maize yield and plant damage by *Busseola fusca* (Fuller) (*Lepidoptera: Noctuidae*) in the humid forest of southern Cameroon. Agric. Ecosyst. Environ. 108, 17–28.

Chala, A., Mohammed, A., Ayalew, A., Skinnes, H., 2013. Natural occurrence of aflatoxins in groundnut (*Arachis hypogaea* L.) from eastern Ethiopia. Food Control 30, 602–605.

Chengappa, P.G., 2004. Emerging trends in agro-processing in India. Indian J. Agric. Econ. 59, 55–74.

Cheruiyot, R.C., Gicharu, G.K., Gitonga, N.M., Boga, H., Maingi, J.M., 2013. Effect of inoculating selected climbing bean cultivars with different rhizobia strains on nitrogen fixation.

Chibarabada, T.P., Modi, A.T., Mabhaudhi, T., 2015. Water use characteristics of a bambara groundnut (*Vigna subterranea* L. Verdc) landrace during seedling establishment. Water SA 41, 472–482.

Chivenge, P., Mabhaudhi, T., Modi, A.T., Mafongoya, P., 2015. The Potential Role of Neglected and Underutilised Crop Species as Future Crops under Water Scarce Conditions in Sub-Saharan Africa. Int. J. Environ. Res. Public Health 12, 5685–711. doi:10.3390/ijerph120605685

Conway, D., Persechino, A., Ardoin-Bardin, S., Hamandawana, H., Dieulin, C., Mahé, G., 2009. Rainfall and water resources variability in sub-Saharan Africa during the twentieth century. J. Hydrometeorol. 10, 41–59.

Coomes, O.T., McGuire, S.J., Garine, E., Caillon, S., McKey, D., Demeulenaere, E., Jarvis, D., Aistara, G., Barnaud, A., Clouvel, P., 2015. Farmer seed networks make a limited contribution to agriculture? Four common misconceptions. Food Policy 56, 41–50.

Crépon, K., Marget, P., Peyronnet, C., Carrouée, B., Arese, P., Duc, G., 2010. Nutritional value of faba bean (*Vicia faba* L.) seeds for feed and food. F. Crop. Res. 115, 329–339.

Crews, T.E., Peoples, M.B., 2004. Legume versus fertilizer sources of nitrogen: ecological tradeoffs and human needs. Agric. Ecosyst. Environ. 102, 279–297.

Deka, R.K., Sarkar, C.R., 1990. Nutrient composition and antinutritional factors of *Dolichos lablab* L. seeds. Food Chem. 38, 239–246. doi:10.1016/0308-8146(90)90180-C

Deshpande, S.S., 2000. Fermented Grain Legumes, Seeds and Nuts: A Global Perspective, Issue 142. Food & Agriculture Org. Rome.

Diaz Rios, L., 2008. Barrier, catalyst, or distraction? Standards, competitiveness, and Africa's groundnut exports to Europe.

Divito, G.A., Sadras, V.O., 2014. How do phosphorus, potassium and sulphur affect plant growth and biological nitrogen fixation in crop and pasture legumes? A meta-analysis. F. Crop. Res. 156, 161–171.

Dixon, R.M., Hosking, B.J., 1992. Nutritional value of grain legumes for ruminants. Nutr. Res. Rev. 5, 19–43.

Duc, G., Agrama, H., Bao, S., Berger, J., Bourion, V., De Ron, A.M., Gowda, C.L.L., Mikic, A., Millot, D., Singh, K.B., Tullu, A., Vandenberg, A., Vaz Patto, M.C., Warkentin, T.D., Zong, X., 2015. Breeding Annual Grain Legumes for Sustainable Agriculture: New Methods to Approach Complex Traits and Target New Cultivar Ideotypes. CRC. Crit. Rev. Plant Sci. 34, 381–411. doi:10.1080/07352689.2014.898469

Dugje, I.Y., Omoigui, L.O., Ekeleme, F., Bandyopadhyay, R., Kumar, P.L., Kamara, A.Y., 2009. Farmers' guide to soybean production in northern Nigeria. IITA.

Ezumah, N.N., Di Domenico, C.M., 1995. Enhancing the role of women in crop production: A case study of Igbo women in Nigeria. World Dev. 23, 1731–1744.

Faber, M., Venter, S.L., Benadé, A.J.S., 2002. Increased vitamin A intake in children aged 2–5 years through targeted home-gardens in a rural South African community. Public Health Nutr. 5, 11–16.

FAO, 2015. The State of Food and Agriculture 2015. Social Protection and Agriculture: Breaking the Cycle of Rural Poverty, in: SOFA. p. 151.

FAO, 1996. The Rome declaration on world food security. Popul. Dev. Rev. 22, 14–17. doi:10.2307/2137827

FAO, IFAD, WFP, 2015. The State of Food Insecurity in the World: Meeting the 2015 international hunger targets: taking stock of uneven progress, FAO, IFAD and WFP. FAO. doi:I4646E/1/05.15

Food and Agriculture Organization, 1997. The State of Food and Agriculture. Rome.

Foyer, C.H., Lam, H.-M., Nguyen, H.T., Siddique, K.H.M., Varshney, R.K., Colmer, T.D., Cowling, W., Bramley, H., Mori, T.A., Hodgson, J.M., 2016. Neglecting legumes has compromised human health and sustainable food production. Nat. Plants 2, 16112.

Geil, P.B., Anderson, J.W., 1994. Nutrition and health implications of dry beans: a review. J. Am. Coll. Nutr. 13, 549–558.

Gemede, H.F., Ratta, N., 2014. Antinutritional factors in plant foods: potential health benefits and adverse effects. Glob. Adv. Res. J. Food Sci. Technol 3, 103–117.

Gepts, P., Beavis, W.D., Brummer, E.C., Shoemaker, R.C., Stalker, H.T., Weeden, N.F., Young, N.D., 2005. Legumes as a model plant family. Genomics for food and feed report of the cross-legume advances through genomics conference. Plant Physiol. 137, 1228–1235.

Gilani, G.S., Xiao, C.W., Cockell, K.A., 2012. Impact of antinutritional factors in food proteins on the digestibility of protein and the bioavailability of amino acids and on protein quality. Br. J. Nutr. 108, S315–S332.

Giller, K.E., Murwira, M.S., Dhliwayo, D.K.C., Mafongoya, P.L., Mpepereki, S., 2011. Soyabeans and sustainable agriculture in southern Africa. Int. J. Agric. Sustain. 9, 50–58.

Graeub, B., Chappell, M., Wittman, H., Ledermann, S., Kerr, R., Gemmill-Herre, B., 2015. The State of Family Farms in the World. World Development in press. World Dev. doi:10.1016

Güzel, D., Sayar, S., 2012. Effect of cooking methods on selected physicochemical and nutritional properties of barlotto bean, chickpea, faba bean, and white kidney bean. J. Food Sci. Technol. 49, 89–95. doi:10.1007/s13197-011-0260-0

Haan, A. de, 1997. Rural- Urban Migration and Poverty: The Case of India. IDS Bull. 28, 35–47.

Hamama, A.A., Bhardwaj, H.L., 2002. Tepary bean: A short duration summer crop in Virginia. Trends new Crop. New uses. ASHS Press. Alexandria, VA 429–431.

Hatcher, P., Battey, N., 2011. Biological Diversity: Exploiters and Exploited. John Wiley & Sons.

Heathcote, J.G., Hibbert, J.R., 1978. Aflatoxins: chemical and biological aspects.

Huisman, J., Van der Poel, A.F.B., 1994. Aspects of the nutritional quality and use of cool season food legumes in animal feed, in: Expanding the Production and Use of Cool Season Food Legumes. Springer, pp. 53–76.

Hutchinson, J., 1969. Evolution and phylogeny of flowering plants.

ICRISAT, CIAT, ICARDA, IITA, 2012. Grain legumes: Leveraging legumes to combat poverty, hunger, malnutrition and environmental degradation.

Igbadun, H.E., Mahoo, H.F., Tarimo, A.K.P.R., Salim, B.A., 2006. Crop water productivity of an irrigated maize crop in Mkoji sub-catchment of the Great Ruaha River Basin, Tanzania. Agric. Water Manag. 85, 141–150.

International Food Policy Research Institute, n.d. Global Nutrition Report 2014: Actions and Accountability to Accelerate the World's Progress on Nutrition. Washington DC.

International Monetary Fund, 2014. The Gambia: Poverty reduction strategy paper- Progress report. Washington DC.

Iqbal, A., Khalil, I.A., Ateeq, N., Khan, M.S., 2006. Nutritional quality of important food legumes. Food Chem. 97, 331–335.

Jezierny, D., Mosenthin, R., Bauer, E., 2010. The use of grain legumes as a protein source in pig nutrition: A review. Anim. Feed Sci. Technol. 157, 111–128.

Joint, F.A.O., Organization, W.H., 2005. Vitamin and mineral requirements in human nutrition.

Jones, R.B., Audi, P.A., Tripp, R., 2001. The Role of Informal Seed Systems in Disseminating Modern Varieties. The Example of Pigeonpea from a Semi-aridArid Area of Kenya. Explor. Agric. 37, 539–548. doi:10.1017/S0014479701000461

Kachru, R.P., 2010. Agro-processing industries in India—growth, status and prospects. J. Indones. Agroindustries 13.

Karpenstein-Machan, M., Stuelpnagel, R., 2000. Biomass yield and nitrogen fixation of legumes monocropped and intercropped with rye and rotation effects on a subsequent maize crop. Plant Soil 218, 215–232.

Kat, J., Diop, A., Gergeley, N., 1992. Guidelines for the Establishment, Operation, and Management of Cereal Banks, Issues 83-88. Food & Agriculture Org.

Kearney, J., 2010. Food consumption trends and drivers. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 365, 2793–807. doi:10.1098/rstb.2010.0149

Kerr, R.B., 2012. Lessons from the old Green Revolution for the new: Social, environmental and nutritional issues for agricultural change in Africa. Prog. Dev. Stud. 12, 213–229.

Khan, M.A., 1987. Nutritional attributes of food legumes. Progress. Farming.

Liu, K., 1997. Chemistry and nutritional value of soybean components, in: Soybeans. Springer, pp. 25–113.

Luchese, R.H., Harrigan, W.F., 1993. Biosynthesis of aflatoxin—the role of nutritional factors. J. Appl. Bacteriol. 74, 5–14.

Mabhaudhi, T., Chibarabada, T., Modi, A., 2016. Water-Food-Nutrition-Health Nexus: Linking Water to Improving Food, Nutrition and Health in Sub-Saharan Africa. Int. J. Environ. Res. Public Health 13, 107.

Mabhaudhi, T., Modi, A., Beletse, Y., 2013. Growth, phenological and yield responses of a bambara groundnut (*Vigna subterranea* L. Verdc) landrace to imposed water stress: II. Rain shelter conditions. Water SA 39, 191–198.

Mahadevamma, S., Tharanathan, R.N., 2004. Processing Of Legumes: Resistant Starch and Dietary Fiber Contents. J. Food Qual. 27, 289–303. doi:10.1111/j.1745-4557.2004.00620.x

Manay, N., Swamy, S., 2001. Food: Facts and Principles 2nd Edition, 2nd Ed. New Age International, New Delhi.

Martin, S.G., Acker, R.C. Van, Friesen, L.F., 2009. Critical period of weed control in spring canola.

Mathews, C., Saxena, K.B., 2005. Prospects for pigeon pea cultivation in drought-prone areas of South Africa. Proc. First Int. Edible Legum. Conf. Conjunction with IVth World Cowpea Congr. 1–11.

McCormack, J.H., 2004. Seed processing and storage: principles and practices of seed harvesting, processing, and storage: an organic seed production manual for seed growers in the Mid-Atlantic and Southern US. Carolina Farm Steward. Assoc. Pittsboro (NC) (2004 Dec.) [Garden Med. Culinaries, Earlysville, VA].

McDermott, J., Johnson, N., Kadiyala, S., Kennedy, G., Wyatt, A.J., 2015. Agricultural research for nutrition outcomes–rethinking the agenda. Food Secur. 7, 593–607.

McKevith, B., 2004. Nutritional aspects of cereals. Nutr. Bull. 29, 111–142.

Meiners, C.R., Derise, N.L., Lau, H.C., Crews, M.G., Ritchey, S.J., Murphy, E.W., 1976. The content of nine mineral elements in raw and cooked mature dry legumes. J. Agric. Food Chem. 24, 1126–1130.

Messina, M.J., 1999. Legumes and soybeans: overview of their nutritional profiles and health effects. Am. J. Clin. Nutr. 70, 439s–450s.

Mhango, W.G., Snapp, S.S., Phiri, G.Y.K., 2013. Opportunities and constraints to legume diversification for sustainable maize production on smallholder farms in Malawi. Renew. Agric. Food Syst. 28, 234–244.

Modi, M., Modi, A., Hendriks, S., 2006. Potential role for wild vegetables in household food security: a preliminary case study in Kwazulu-Natal, South Africa. African J. Food, Agric. Nutr. Dev. 6, 1–13.

Molden, D., 2007. Water for food, water for life - A Comprehensive Assessment of Water Management in Agriculture, Water Management.

Molden, D., Murray-Rust, H., Sakthivadivel, R., Makin, I., 2003. A water-productivity framework for understanding and action. Water Product. Agric. Limits Oppor. Improv.

Mooney, H., Drake, J., 2012. Ecology of Biological Invasions of North America and Hawaii. Springer Science & Business Media.

Mothander, B., Kjærby, F., Havnevik, K.J., 1989. Farm implements for smallholder farmers in Tanzania. Nordic Africa Institute.

Muigai, C., Ogana, F., B, S., Simtowe, F., Asfaw, S., n.d. Integrated innovations for improving Legume Productivity, Market Linkages and Risk Management in Eastern and Southern Africa. Seed Production and Marketing: A handbook for Farmer organizations and Agro-enterprises.

Muñoz-Perea, C.G., Allen, R.G., Westermann, D.T., Wright, J.L., Singh, S.P., 2007. Water use efficiency among dry bean landraces and cultivars in drought-stressed and non-stressed environments. Euphytica 155, 393–402. doi:10.1007/s10681-006-9340-z

Mweetwa, A.M., Mulenga, M., Mulilo, X., Ngulube, M., Banda, J.S.K., Kapulu, N., N'gandu, S.H., 2014. Response of Cowpea, Soya Beans and Groundnuts to Non-Indigenous Legume Inoculants. Sustain. Agric. Res. 3, 84.

Nedumaran, S., Abinaya, P., Jyosthnaa, P., Shraavya, B., Rao, P., Bantilan, C., 2015. Grain Legumes Production, Consumption and Trade Trends in Developing Countries; Working Paper Series No. 60.

Nji, F.F., Niess, E., Pfeffer, E., 2004. Nutrient content of Bambara groundnut (*Vigna subterranea*) and the effects of its inclusion on the performance of growing broiler chickens and on egg production and quality. J. Anim. Feed Sci. 13, 497–507.

Obalum, S.E., Igwe, C.A., Obi, M.E., Wakatsuki, T., 2011. Water use and grain yield response of rainfed soybean to tillage-mulch practices in southeastern Nigeria. Sci. Agric. 68, 554–561.

Odeny, D.A., Jayashree, B., Ferguson, M., Hoisington, D., Crouch, J., Gebhardt, C., 2007. Development, characterization and utilization of microsatellite markers in pigeonpea. Plant Breed. 126, 130–136. doi:10.1111/j.1439-0523.2007.01324.x

OECD, FAO, 2015. OECD-FAO Agricultural Outlook 2015. Paris.

Olorunmaiye, P.M., 2010. Weed control potential of five legume cover crops in maize/cassava intercrop in a Southern Guinea savanna ecosystem of Nigeria. Aust. J. Crop Sci. 4, 324.

Oppen, M. von, 1981. Prospects for grain legume production in Asia. International Crops Research Institute for the Semi-aridArid Tropics (ICRISAT). Andhra Pradesh, IN.

Oweis, T., 1997. Supplemental irrigation: A highly efficient water-use practice. ICARDA.

Patel, G.N., Patel, P.T., Patel, P.H., 2008. Yield, water use efficiency and moisture extraction pattern of summer.

Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci. Discuss. 4, 439–473.

Pingali, P.L., 2012. Green revolution: impacts, limits, and the path ahead. Proc. Natl. Acad. Sci. U. S. A. 109, 12302–8. doi:10.1073/pnas.0912953109

Reckling, M., Hecker, J.-M., Bergkvist, G., Watson, C.A., Zander, P., Schläfke, N., Stoddard, F.L., Eory, V., Topp, C.F.E., Maire, J., 2015. A cropping system assessment framework—evaluating effects of introducing legumes into crop rotations. Eur. J. Agron.

Reddy, R., Nigam, S.N., Parthasarthy, R., Ahmed, S., Ratnakar, R., Alur, S., Ashok, K.A., 2010. Village Seed Banks: An integrated seed system for improved seed production and supply – A case study. International Crops Research Institute for the Semi-aridArid Tropics, Patancheru.

Rockström, J., 2003. Water for food and nature in drought–prone tropics: vapour shift in rain–fed agriculture. Philos. Trans. R. Soc. London B Biol. Sci. 358, 1997–2009.

Rockström, J., Karlberg, L., Wani, S.P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., Qiang, Z., 2010. Managing water in rainfed agriculture—the need for a paradigm shift. Agric. Water Manag. 97, 543–550.

Rubiales, D., Fernández-Aparicio, M., 2011. Innovations in parasitic weeds management in legume crops. A review. Agron. Sustain. Dev. 32, 433–449. doi:10.1007/s13593-011-0045-x

Rühlemann, L., Schmidtke, K., 2015. Evaluation of monocropped and intercropped grain legumes for cover cropping in no-tillage and reduced tillage organic agriculture. Eur. J. Agron. 65, 83–94.

Saeed, I.A.M., El-Nadi, A.H., 1998. Forage sorghum yield and water use efficiency under variable irrigation. Irrig. Sci. 18, 67–71. doi:10.1007/s002710050046

Sanchez, P.A., 2002. Soil fertility and hunger in Africa. Science (80-.). 295, 2019–2020.

Seena, S., Sridhar, K.R., 2005. Physicochemical, functional and cooking properties of under explored legumes, Canavalia of the southwest coast of India. Food Res. Int. 38, 803–814.

Sharma, S., Upadhyaya, H.D., Varshney, R.K., Gowda, C.L.L., 2013. Pre-breeding for diversification of primary gene pool and genetic enhancement of grain legumes. Front. Plant Sci. 4, 309.

Sheerens, J.C., Tinsley, A.M., Abbas, I.R., Weber, C.W., Berry, J.W., 1983. The nutritional significance of tepary bean consumption. Desert plants.

Shetty, P., 2015. From food security to food and nutrition security: role of agriculture and farming systems for nutrition. Curr. Sci. 109, 456–461.

Siddhuraju, P., Becker, K., Makkar, H.P.S., 2000. Studies on the nutritional composition and antinutritional factors of three different germplasm seed materials of an under-utilized tropical legume, *Mucuna p ruriens* Var. U tilis. J. Agric. Food Chem. 48, 6048–6060.

Siddique, K.H.M., Regan, K.L., Tennant, D., Thomson, B.D., 2001. Water use and water use efficiency of cool season grain legumes in low rainfall Mediterranean-type environments. Eur. J. Agron. 15, 267–280.

Singh, K.M., Singh, A.K., 2014. Lentil in India: An Overview. Available SSRN 2510906.

Singh, K.P., Srivastva, A.K., Srinivas, K., Singh, S.R.K., Gupta, H.S., 2007. Entrepreneurship development in agriculture through agro processing centre: a case study of Almora district in NW Himalaya. Agric. Eng. Int. CIGR J.

Singh, U., Jain, K.C., Jambunathan, R., Faris, D.G., 1984. Nutritional quality of vegetable pigeonpeas [*Cajanus cajan* (L.) Mill sp.]: mineral and trace elements. J. Food Sci. 49, 645–646.

Singh, U., Singh, B., 1992. Tropical grain legumes as important human foods. Econ. Bot. 46, 310–321.

Smartt, J., 2012. The groundnut crop: a scientific basis for improvement. Springer Science & Business Media.

Smartt, J., 1990. Grain Legumes: Evolution and Genetic Resources. Cambridge University Press.

Smartt, J., 1976. Tropical pulses.

Smith, A., Snapp, S., Dimes, J., Gwenambira, C., Chikowo, R., 2016. Doubled-up legume rotations improve soil fertility and maintain productivity under variable conditions in maize-based cropping systems in Malawi. Agric. Syst. 145, 139–149.

Smith, T.M., Kolars, J.C., Savaiano, D.A., Levitt, M.D., 1985. Absorption of calcium from milk and yogurt. Am. J. Clin. Nutr. 42, 1197–200.

Subuola, F., Widodo, Y., Kehinde, T., 2012. Processing and Utilization of Legumes in the Tropics. Trends Vital Food Control Eng. Rijeka, Croat. InTech 71.

Sumberg, J., 2002. The logic of fodder legumes in Africa. Food Policy 27, 285–300.

Summerfield, J., 2012. World crops: Cool season food legumes: A global perspective of the problems and prospects for crop improvement in pea, lentil, faba bean and chickpea. Springer Science & Business Media.

Sur, S., Bothra, A.K., Sen, A., 2010. Symbiotic Nitrogen Fixation-A Bioinformatics Perspective. Biotechnology 9, 257–273.

Swanevelder, C.J., 1998. Bambara groundnuts- food for Africa. South Africa.

Thompson, B., Amoroso, L., Meerman, J., n.d. Promoting the Expression “Food and Nutrition Security (FNS)”. A Strategy note from the Nutrition and Consumer Protection Division – AGN.

Tijani, F.O., Oyedele, D.J., Aina, P.O., 2008. Soil moisture storage and water-use efficiency of maize planted in succession to different fallow treatments. Int. Agrophysics 22, 81.

Timmer, C.P., 1995. Getting agriculture moving: do markets provide the right signals? Food Policy 20, 455–472.

Toensmeier, E., 2007. Perennial Vegetables: From Artichoke to Zuiki Taro, a Gardener’s Guide to Over 100 Delicious, Easy-to-grow Edibles. Chelsea Green Publishing.

UNICEF, 2015. A wake-up call: El Niño’s impact on children. Briefing note.

UNICEF, WHO, Worldbank, 2014. Child malnutrition indicators (stunting, wasting, severe wasting, overweight and underweight) and new global & regional estimates for 2013.

USAID, 2012. Burundi legume/bean value chain rapid analysis.

USDA, n.d. No Title [www Document]. White Lupine (*Lupinus albus* L.) URL https://plants.usda.gov/plantguide/pdf/pg_lual22.pdf (accessed 10.29.16).

Valenzuela, H., Smith, J., 2002. Sustainable agriculture green manure crops.

van Halsema, G.E., Vincent, L., 2012. Efficiency and productivity terms for water management: A matter of contextual relativism versus general absolutism. Agric. Water Manag. 108, 9–15.

Večerek, V., Suchý, P., Straková, E., Macháček, M., Palta, J.A., Berger, J.D., 2008. Nutritive composition of seeds of the lupin varieties registered in the Czech Republic, in: Lupins for Health and Wealth' Proceedings of the 12th International Lupin Conference. pp. 14–18.

Vimalendran, L., Latha, K.R., 2014. Yield, water use and water use efficiency of pigeonpea [*Cajanus cajan* (L.) Millsp.] under drip fertigation system.

Watanabe, M., Jinji, N., Kurihara, M., 2009. Is the development of the agro-processing industry pro-poor?: The case of Thailand. J. Asian Econ. 20, 443–455.

Wekundah, J.M., 2012. Why Informal Seed Sector is Important in Food Security, African Technology Policy Studies Network Biotechnology Trust Africa: Special Paper series No. 43.

Williams, B., 1994. Grain Legume Harvesting [WWW Document]. South. Mallee Northen Wimmera Crop Pasture Man. URL file:///C:/Users/212512302/Downloads/grain_legume_harvesting_1994.pdf (accessed 8.5.15).

Wojcicki, J.M., 2014. The double burden household in sub-Saharan Africa: maternal overweight and obesity and childhood undernutrition from the year 2000: results from World Health Organization Data (WHO) and Demographic Health Surveys (DHS). BMC Public Health 14, 1.

World Bank Open Data [WWW Document], n.d. URL data.worldbank.org

www.dpi.nsw.gov.au, n.d. Faba bean [www Document]. URL http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0004/157729/faba-bean-pt1.pdf www.icrisat.org, n.d. No Title [WWW Document]. URL http://exploreit.icrisat.org/page/projects/708 (accessed 7.10.15).

www.iita.org, n.d. No Title [www Document]. URL www.iita.org.http://www.iita.org/geneticresources;jsessionid=DACC1285D353484D2DA69BA9F2CEB4DB (accessed 9.14.15).

www.nda.agric.za, n.d. Dry beans production guideline [www Document]. URL http://www.nda.agric.za/docs/Brochures/Dry-beans.pdf (accessed 5.10.15a).

www.nda.agric.za, n.d. Chickpea [www Document]. URL http://www.nda.agric.za/docs/Brochures/Chickpea.pdf (accessed 5.10.15b).

www.pea-lentil.com, n.d. USA Dry Pea, Lentil & Chickpea Production [www Document]. URL http://www.pea-lentil.com/core/files/pealentil/uploads/files/Chapter3.pdf. (Accessed 10.15.15).

www.tradeforum.org, n.d. Exporting groundnuts [www Document]. URL http://www.tradeforum.org/exporting-groundnuts. (Accessed 9.20.15).

Yao, D.N., Kouassi, K.N., Erba, D., Scazzina, F., Pellegrini, N., Casiraghi, M.C., 2015. Nutritive Evaluation of the Bambara Groundnut Ci12 Landrace [*Vigna subterranea* (L.) Verdc. (Fabaceae)] Produced in Côte d'Ivoire. Int. J. Mol. Sci. 16, 21428–21441.

Zahran, H.H., 1999. Rhizobium-legume symbiosis and nitrogen fixation under severe conditions and in an arid climate. Microbiol. Mol. Biol. Rev. 63, 968–89, table of contents.

Zeven, A.C., 1998. Landraces: a review of definitions and classifications. Euphytica 104, 127–139.

Zhang, H., Pala, M., Oweis, T., Harris, H., 2000. Water use and water-use efficiency of chickpea and lentil in a Mediterranean environment. Aust. J. Agric. Res. 51, 295–304. doi:10.1071/AR99059

CHAPTER 4

WATER USE CHARACTERISTICS OF HYBRID, OPEN-POLLINATED, AND LANDRACE SORGHUM GENOTYPES UNDER RAINFED CONDITIONS

Hadebe, S.T., Modi, A.T. and Mabhaudhi, T.

4.1 Introduction

Sub-Saharan Africa (SSA) faces twin challenges of water scarcity and food insecurity and these challenges are projected to increase. Within the region, rainfed agriculture constitutes more than 95% of agricultural land use (Singh et al., 2011), making water availability the single most important factor in crop production. Neither of these challenges can be addressed in isolation (Postel, 2003; Rosegrant et al., 2009). Strategies to produce 'more food per drop' (Molden et al., 2010) have been considered in a variety of ways. These have included identifying areas of water availability, water stress (Brauman et al., 2013), impacts of water use and projections of future water scarcity (Ringler et al., 2011; Murray et al., 2012). Any improvement in crop water productivity will have a positive effect on either food production or water savings (Brauman et al., 2013). Therefore, strategies to increase food productivity while conserving water have become increasingly important (Giovannucci et al., 2012). Among these strategies is selection of drought and heat tolerant crops, and screening of genotypes for high water use efficiency (WUE).

Drought stress is one of the most limiting factors for cereal crop yield. Drought and heat tolerance make sorghum unique among major cereal crops, suited for cultivation as staple food in arid agro-ecological regions of SSA (Hattori et al., 2005; Staggenborg et al., 2008). It is the second most cultivated cereal crop in SSA and ranks first in the semi–arid Sahel (FAOSTAT, 2013). Although sorghum originated in SSA, where comparatively striking drought tolerance and superior WUE have developed in the species, there is a need to harness these traits to positively contribute to food production, especially in arid and semi–arid regions. The available genetic resources in sorghum are still relatively under-exploited (Rosenow and Dahlberg, 2000; Kapanigowda et al., 2013). Moreover, rain-fed sorghum farming systems differ in SSA. Both well-resourced commercial farmers and resource-constrained smallholder farmers cultivate sorghum. The management practices under these two farming systems markedly differ, with high management practices by commercial farmers and low crop management by smallholder farmers. Crop management has implications on crop yield, hence WUE.

Crop production in SSA, specifically staple cereal crop production, needs to adapt to water scarcity and improve water productivity to meet food requirements. Sorghum's drought, heat and flood tolerance as well as high and stable WUE make it an ideal crop for production in SSA. However, studies of sorghum WUE and response of secondary traits associated with drought tolerance to water availability in rain-fed agroecologies in SSA are lacking. Hence, this study investigated genotype-by-environment and water use characteristics of three sorghum genotypes covering the large genetic range between landrace and hybrid. Specific objectives were to determine (i) morpho-physiological and phenological responses of three sorghum genotypes to different agroecologies and management practices, (ii) yield responses of three sorghum genotypes to different agro–ecological conditions, and (iii) WUE responses for the three sorghum cultivars to different agro–ecological conditions and management practices.

4.2 Materials and Methods

4.2.1 Plant material

Three genotypes, a hybrid, an open-pollinated variety and a landrace, were selected for this study. This reflected the range of germplasm typically used by farmers for sorghum production in Southern Africa. The hybrid was PAN8816, which represented the preferred seed variety by commercial sorghum farmers. PAN8816 was supplied by Pannar Seeds®. It is a bronze-grained, medium to late maturing, low tannin sorghum hybrid. Flowering occurs at approximately 71 days after sowing. It is renowned for good leaf disease and head smut resistance.

Macia is a popular low tannin, open-pollinated variety developed by the International Crop Research Institute for the Semi–Arid Tropics (ICRISAT). It is grown in most sorghum growing regions across SSA (Takele and Farrant, 2013; Charyulu et al., 2015). It is an early to medium maturing (60-65 days to heading and 115-120 days to maturity), semi–dwarf (1.3–1.5 m tall with thick stem) variety. It has a wide growing rainfall range (250–750 mm) during the growing season, with stay green characteristics extending beyond harvest. Grain yield potential is 3000 – 6000 kg ha^{-1} of dry matter.

Ujiba is a high tannin landrace representing a popular seed choice among subsistence farmers. It was sourced locally from smallholder farmers in Tugela Ferry (28°44'S, 30°27'E), South Africa. For the landrace, phenological, morphological and physiological information were lacking.

4.2.2 Site description

Field trials were planted at two locations – Ukulinga (30°24'S, 29°24'E, 805 m a.s.l) and Umbumbulu (29°59'S, 30°42'E, 548 m a.s.l), South Africa, in 2013/14 and 2014/15. Ukulinga is a well-equipped agricultural research farm, whilst Umbumbulu is a resource–constrained rural setting. In addition, these two locations also offered two different microclimates despite being classified under the same bioresource group (Table 3. 1). Bioresource groups (BRGs), are defined as specific vegetation types characterized by an interplay of climate, altitude and soil factors. Soil physical and hydraulic properties were obtained from classification and characterization of experimental site soils by Mabhaudhi (2012). These include volumetric water content at field capacity (FC), at permanent wilting point (PWP), and at saturation (SAT), saturated hydraulic conductivity (K_{sat}), total available water (TAW) and soil depth (Table 4.1).

Table 4.1: Bio–resource group classification, climate, and soil physical and hydraulic properties of Umbumbulu and Ukulinga planting sites.

Site	Annual rainfall	Average temperature	Soil form	Clay	^{w}FC	^{x}PWP	^{y}SAT	Soil profile depth	^{z}Ksat
	(mm)	(˚C)		%	——(% Volumetric)——			(m)	(mm day^{-1})
Ukulinga	694	17.0	Vertisols	< 29	40.6	23	48.1	0.6	25.0
Umbumbulu	1009	17.9	Oxisols	> 60	45.1	34.5	51.0	1.5	79.7

^{w}FC = Field capacity
^{x}PWP = Permanent wilting point
^{y}SAT = Saturation
^{z}Ksat = Saturated hydraulic conductivity

4.2.3 Trial layout and design

Field trials were conducted in the two above mentioned planting sites and seasons, totalling four experiments. At each site, the experimental design used was a randomized complete block design with three replicates. The trials comprised the three above referred sorghum genotypes. The trials measured 310 m^2, with individual plot size of 6 m * 4.5 m (18 m^2), with 1 m wide interplot spacing between the plots. Inter-row spacing was 0.75 m with 0.30 m intra-row spacing, corresponding to 4.4 plants per m^2, and to 21 plants per row. Each individual plot had seven rows with the three inner most rows as the experimental plants, and the second and fifth rows reserved for destructive sampling. Planting rows were dug ≈25 mm deep; seeds were sown closely and thinned to the desired crop density after establishment.

4.2.4 Data collection

At both locations, daily meteorological data including minimum and maximum temperature, rainfall, maximum and minimum relative humidity, wind speed and direction, solar radiation and reference evapotranspiration were collected. At Ukulinga, data were obtained from an on–station (within 100 m radius) automatic weather station (AWS), courtesy of the Agricultural Research Council–Institute for Soil, Climate and Water (ARC–ISCW). For Umbumbulu, meteorological data was obtained from an AWS (within 6 km radius), courtesy of the South African Sugar Research Institute (SASRI) (http://sasri.sasa.org.za/irricane/tables/).

Observations of crop physiology, morphology and phenology were taken weekly at Ukulinga and fortnightly in Umbumbulu. Seedling emergence was considered as coleoptile protrusion above soil surface. Emergence was scored from sowing until establishment (90% emergence). Plant height was measured from establishment using a tape measure as distance from soil surface to the tip of the youngest developing leaf (before floral initiation) or tip of the growing panicle thereafter. Leaf number was counted for fully expanded and photosynthetically active (50% green leaf area) leaves from establishment (Mabhaudhi and Modi, 2013). A fully formed leaf was defined as when the leaf collar was visible without dissecting the plant. The flag-leaf was counted as the first leaf upon full formation. Canopy cover (CC) was measured using the LAI2200 canopy analyser (Li–Cor®, USA) fortnightly after crop establishment until physiological maturity. A single measurement was taken above the canopy, and four measurements were taken below the canopy in a one–meter diagonal distance. The four below canopy readings were taken at different positions, namely: between the row, next to the row, in the middle of the rows, and further away from the row. A 90° view cap was used for measurements. Three canopy measurements were done per replicate (plot) and mean values were taken as representative of the plot. Values describing the diffuse non-intercepted radiation (DIFN) which is the amount of light visible below the canopy were taken and converted to percentage canopy cover as described by Mabhaudhi et al., (2014):

$$CC = (1 - DIFN) \times 100\% \qquad \text{Equation 4.1}$$

Chlorophyll content index (CCI) was measured using a SPAD-502 *Plus* chlorophyll meter (Konica Minolta, Osaka, Japan) on the adaxial surface of the first fully expanded, fully exposed leaf at midday (1200–1400 hrs.) fortnightly after crop establishment until physiological maturity. Stomatal conductance (SC) was measured at midday using a SC–1 leaf porometer (Decagon Devices®, Pullman, WA, USA) from the abaxial surface of the first fully expanded, fully exposed leaf at midday (1200–1400 hrs.) fortnightly after crop establishment until physiological maturity. Data on SC was only collected for the second season due to unavailability of equipment in the first season. For measurements of CCI and SC, three plants were tagged per plot at crop establishment from which measurements were conducted throughout the growing season. This resulted in sampling of three leaves per plot. The SC–1 leaf porometer was calibrated as per manual instructions. In the field, each measurement was taken once equilibrium had been achieved between the atmosphere and the porometer.

Biomass accumulation was determined destructively by sampling aboveground shoot mass fortnightly after crop establishment (90% emergence) and oven–drying plant material (80°C for 72 hrs.). Upon flowering (complete panicle exposure), panicle mass and total above ground above biomass (B) were weighed separately to enable determination of build-up of harvest index (HI). Final harvest index was taken as harvest index at harvest maturity. Harvest index was calculated as follows:

$$HI = Y/B \qquad \text{Equation 4.2}$$

where: Y = grain mass, and B = total above ground biomass.

Time taken to reach a phenological stage was recorded in calendar days and later converted to thermal time (growing degree days, GDD) using method 2, as described by McMaster and Wilhelm (1997):

$$GDD = [(T_{max} + T_{min}) / 2] - T_{base} \qquad \text{Equation 4.3}$$

where: T_{max} = maximum daily temperature, T_{min} = minimum daily temperature, and T_{base} = base temperature below which sorghum growth ceases set at 7 °C (Du Plesis, 2008).

Phenological data were collected weekly at Ukulinga and fortnightly in Umbumbulu. Time taken to reach a phenological stage was observed as time taken for 50% of experimental plant population to exhibit stage diagnostic signals. End of juvenile phase was calculated as the difference between sowing time and flag leaf formation. A bulging of the plant stem marked floral initiation. Flowering was marked by panicle bloom. Full pollen shed by the panicle marked anthesis. Formation of soft, milky grains after anthesis was observed as start of grain filling. Appearance of a dark spot on the opposite side of the kernel from the embryo signalled completion of dry matter accumulation, hence physiological maturity.

4.2.5 Crop water use

Soil water content (SWC) was measured every week using a PR2/6 profile probe (Delta–T, Cambridge, UK) up to 1 m soil depth. In Umbumbulu, SWC was calculated to 1 m soil depth. Whereas at Ukulinga, SWC was calculated to 0.6 m due to presence of an impeding layer. Weekly measurements of SWC were then used to compute a soil water balance (Zhao et al., 2004) from sowing to physiological maturity as follows:

$$ET = I + P + C_r - D - R \pm \Delta SWC \qquad \text{Equation 4.4}$$

where: ET = evapotranspiration, I = irrigation added (mm), P = rainfall (mm), C = capillary rise (mm), D = drainage (mm), R = run-off, and ΔSWC = change in soil water content.

Since trials were wholly rainfed, there was no irrigation (I) to be considered. Capillary rise (C) and drainage (D) were considered negligible (Ridolfi et al., 2008). Runoff (R) was also considered negligible in the soil water balance equation, due to sorghum rows orientated across the slope limiting runoff to negligible proportions. Therefore, Equation 3.4 was simplified to

$$ET = P - \Delta SWC \qquad \text{Equation 4.5}$$

Evapotranspiration obtained from Equation 4.5 was used to calculate WUE in Equation 4.6 and 4.7. Water use efficiency refers to the ratio of water used in plant metabolism to water lost by the plant through transpiration and soil evaporation (evapotranspiration). Water use efficiency was calculated for aboveground biomass at physiological maturity and grain yield at harvest maturity using the following equations:

Biomass WUE = B / ET Equation 4.6

Grain WUE = Y/ ET Equation 4.7

where: B = dry aboveground biomass (kg ha^{-1}), and ET = actual field evapotranspiration (mm) obtained from Equation 4.5.

4.2.6 Agronomic practices

At Ukulinga, land that had been lying fallow was mechanically ploughed, disked and rotovated before planting. At Umbumbulu, land that had been lying fallow was mechanically ploughed before planting; there was no disking and rotovation and seedbed preparation was done using hand hoes.

Soil samples were collected and analysed for fertility before land preparation in both sites during both seasons prior to planting. A deficit of rainfed sorghum soil fertility requirements (120 kg ha^{-1}) as outlined in Smith (2006) was applied at both sites using Gromor Accelerator® (30 g kg^{-1} N, 15 g kg^{-1} P and 15 g kg^{-1} K) slow release organic fertilizer, 14 days after sowing (DAS). At Ukulinga, 45 kg ha^{-1} and 48 kg ha^{-1} of fertilizer was applied; at Umbumbulu, 37 kg ha^{-1} and 34 kg ha^{-1} of fertilizer was applied for the first and second season, respectively. This was to meet nitrogen requirements of the soil, as this nutrient was observed as most deficient from soil sample analysis.

Planting lines were opened by hand 25 mm deep and seeds were hand–sown in the ground. Planting was conducted by drilling sorghum seeds, thereafter, seedlings were thinned to required spacing at crop establishment (14 days after planting). At Umbumbulu, the first and second season field trials were planted on 19 December 2013 and 23 September 2014, respectively. At Ukulinga, trails were planted on 17 January 2014 and 17 November 2014 for first and second seasons, respectively. Rainfall attributes are a major factor in determining time of sowing under rainfed agriculture, since rainfall is a sole water input source into the agriculture system. Differences in onset of rainfall between planting seasons and sites accounted largely for time of sowing. Onset of rainfall was relatively earlier in Umbumbulu compared to Ukulinga in both seasons, and earlier in the 2014/15 season compared to 2013/14 season.

Harvesting was conducted at physiological maturity to measure biomass, grain yield and calculate WUE values; and at harvest maturity to measure thousand seed mass. Harvest maturity was observed as when seeds had ≤12.5% seed moisture content measured using a grain moisture meter (Nunes Instruments, Coimbatore, Tamil Nadu). Length of growing seasons differed according to when this was observed for each site and season.

Round-up® was applied to control weeds two weeks before planting. Weeds, pests, and diseases were hand-removed weekly. Cypermethrin was applied to control insect pests one month after planting.

4.2.7 Data analyses

Measured crop parameters were subjected to analysis of variance (ANOVA) using GenStat® 16th edition (VSN International, Hemel Hemstead, UK). To observe the difference between treatments. Means were separated using least significant differences (LSD) at a probability level of 5%.

4.3 Results and Discussion

4.3.1 Agro-ecological climatic conditions

Sorghum upper and lower temperature thresholds differ according to growth stage and agro–ecological region from which a cultivar is adapted. Upper (38°C) and lower (7°C) temperature thresholds for experimental genotypes in this study were set according to local conditions (Huda et al., 1984; Du Plesis, 2008). Minimum and maximum temperatures did not exceed nor go below sorghum growing temperature thresholds at both planting sites in both seasons (Fig 4.1). This implies that crops did not experience heat or cold stress during both growing season at the two planting sites.

In descending order, rainfall received during the growing season (Table 4.2) was second season in Umbumbulu (501 mm), second season at Ukulinga (401 mm), first season in Umbumbulu (295 mm), and first season at Ukulinga (226 mm). Seasonal rainfall was relatively higher at Umbumbulu than Ukulinga. However, the soil clay content at Umbumbulu exceeded 60%, compared to 29% at Ukulinga (Table 4.1). Roots growth is limited by increased clay content in soils resulting in less soil water extraction by crops. Even worse, plant-extractable moisture in clay soils is somewhat less than the soil's physical properties alone would suggest (Whitmore and Whalley, 2009). This implies plant available water was relatively less than received rainfall in Umbumbulu compared to Ukulinga.

During the first growing season, rainfall became irregular and low (Fig 4.1) at both Ukulinga (post 70 DAS) and Umbumbulu (post 105 DAS), which resulted in declining soil water content (Fig 4.2). This could have predisposed the crop to post–anthesis water stress, which has detrimental effects on grain filling and grain yield. Regular rainfall at both planting sites during the second season resulted in consistently high soil water content (Fig 4.2). However, rainfall was relatively higher in Umbumbulu (501 mm) compared to Ukulinga (401 mm) in the second season. While the soil water balance equation used in this experiment assumed negligible runoff, storm events at Ukulinga resulted in recorded rainfall events above the K_{sat} value (Table 4.1).

This possibly resulted in run-off water losses and intermittent water logging of soils. In future, runoff curve numbers should be incorporated into the soil water balance to account for runoff. At Ukulinga, storms occurred 38 DAS in the first season and 104 DAS in the second season. Sorghum is tolerant to waterlogging (Promkhambut et al., 2011) hence, intermittent waterlogging did not affect crop growth and development.

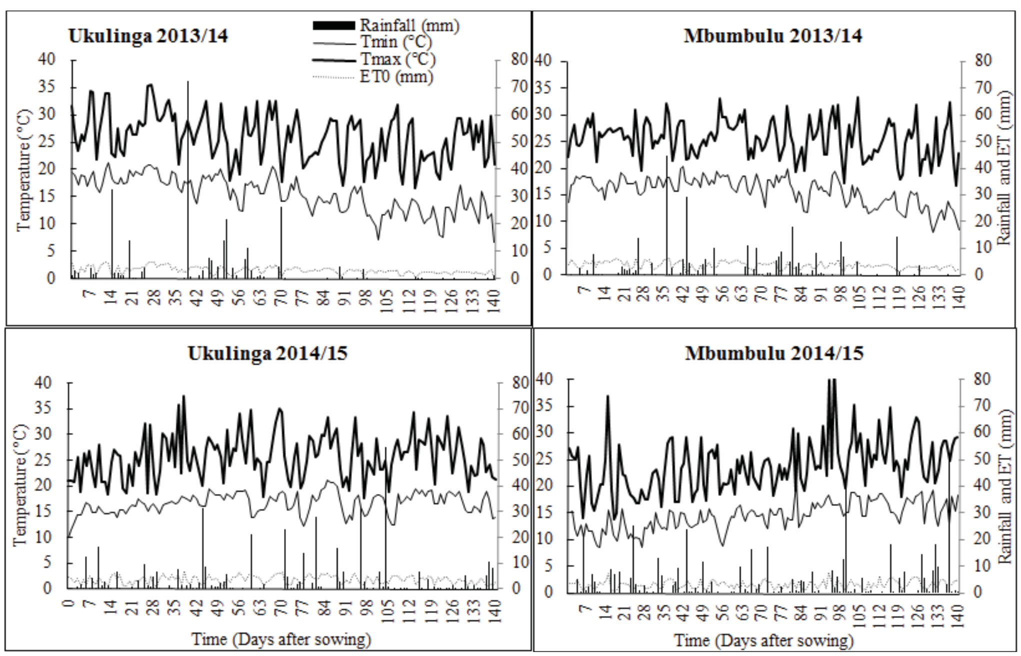

Figure 4.1: Daily rainfall, reference evapotranspiration (ETo), minimum (Tmin) and maximum (Tmax) temperature at Ukulinga and Mbumbulu during 2013/14 and 2014/15 growing seasons.

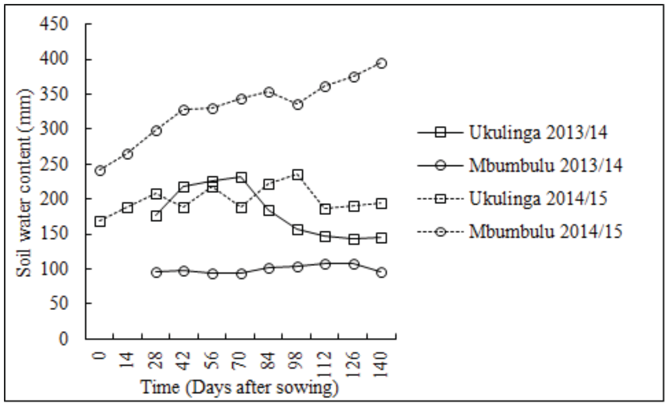

Figure 4.2: Biweekly soil water content measurements at Ukulinga and Umbumbulu during 2013/14 and 2014/15 growing seasons.

Table 4.2: Water use efficiency (WUE) water use characteristics at physiological maturity of three sorghum genotypes planted at two planting sites over two growing seasons.

Season	Site	Genotype	Rainfall received	Water use	Final biomass	Grain yield	Harvest index	Biomass WUE	Grain WUE
			(mm)		(kg.ha^{-1})			(kg.ha^{-1}.mm^{-1})	
First	Ukulinga	PAN8816	226.09	257.69	4600.00	2480.00	0.54	11.78	6.35
		Macia	226.09	257.69	4177.78	2160.00	0.52	10.55	5.46
		Ujiba	226.09	257.69	4982.22	2435.56	0.48	12.58	6.15
		Mean	226.09	257.69	4586.67	2358.52	0.51	11.64	5.99
	Umbumbulu	PAN8816	294.90	293.70	3062.22	1671.11	0.55	10.42	5.69
		Macia	294.90	293.70	4093.33	2564.44	0.63	13.93	8.73
		Ujiba	294.90	293.70	3137.33	1475.56	0.47	10.68	5.02
		Mean	294.90	293.70	3430.96	1903.70	0.55	11.68	6.48
Second	Ukulinga	PAN8816	389.32	364.46	8946.67	4524.44	0.51	24.55	12.41
		Macia	401.25	389.56	12031.11	6160.00	0.60	26.27	15.81
		Ujiba	389.32	364.46	9008.89	3773.33	0.42	24.72	10.35
		Mean	393.30	372.83	9995.56	4819.26	0.51	26.72	12.86
	Umbumbulu	PAN8816	500.50	347.80	6306.67	3351.11	0.53	18.14	9.64
		Macia	500.50	347.80	6066.67	3173.33	0.52	17.44	9.12
		Ujiba	500.50	347.80	5128.89	2355.56	0.46	14.75	6.77
		Mean	500.5	347.80	5834.08	2960.00	0.50	16.77	8.51
LSD					2060.89	1228.89	0.09	6.73	4.00
CV%					5.3	7.7	5.4	6.0	8.5

4.3.2 Crop morphology and physiology

The interaction between seasons, planting sites and genotypes significantly ($P<0.05$) affected leaf number (Fig 4.3). Leaf number was affected ($P<0.001$) by season and site interaction. However, leaf number was statistically similar among genotypes. Mitosis and leaf appearance rate are turgor driven processes that are sensitive to plant available water. Despite relatively high rainfall at Umbumbulu compared to Ukulinga during each of the growing seasons, leaf number was lower in Umbumbulu. High soil water retention by the clayey soils at Umbumbulu decreased plant available water (PAW) and affected growth and development for all sorghum genotypes. This effect was more pronounced under severely low soil water content during the first season. Under water stress, sorghum favours root growth at the expense of shoot and leaf growth (Hsiao and Xu, 2000) to increase soil water capture. Low plant available water at Umbumbulu therefore resulted in decreased leaf number. At both planting sites, the season with low rainfall resulted in lower leaf numbers.

Significant ($P<0.001$) genotypic variations were observed for plant height. With respect to maximum plant height, Ujiba was tallest (≈1.6 m); Macia and PAN8816 were significantly shorter (≈1.2 m) (Fig 4.4). PAN8816 and Macia have been bred as dwarf genotypes; therefore, maximum height is genetically predetermined. The tall, Ujiba landrace was susceptible to lodging. Short genotypes (Macia and PAN8816) were susceptible to panicle destruction by large birds (e.g. guinea fowls) as the head was within reach. Plant height of sorghum genotypes differed significantly ($P<0.001$) between seasons and planting sites. Consistent with observations of leaf number, low soil water availability at Umbumbulu in the first season resulted in stunted plant growth. Cell division and expansion/elongation are both turgor driven processes hence the observed stunted growth at Umbumbulu (Farooq et al., 2009; Silva et al., 2014).

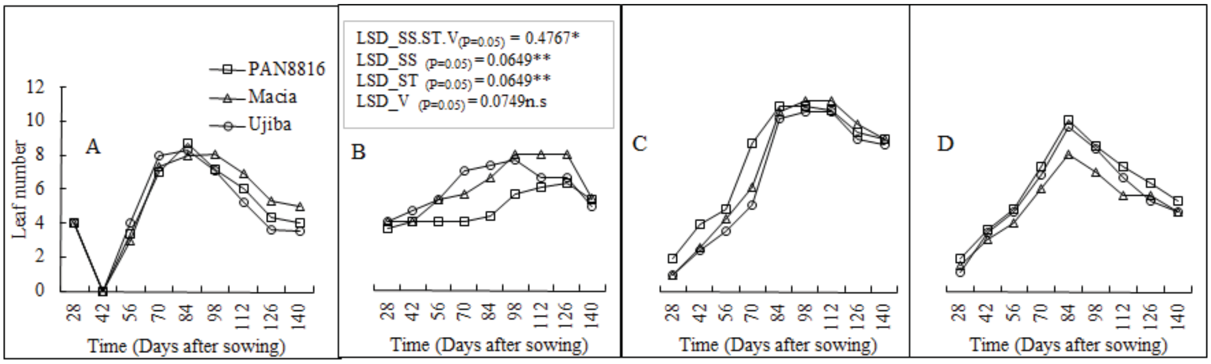

Figure 4.3: Leaf number in PAN8816, Macia and Ujiba sorghum varieties planted at Ukulinga (A and C) and Umbumbulu (B and D) during 2013/14 and 2014/15 growing seasons respectively. Note: SS.ST.V refers to the interaction between growing season (SS), planting site (ST) and sorghum varieties (V). SS refers to growing season, ST refers to planting site, while V refers variety. Means were separated by least significant values (LSD) at P= 0.05.

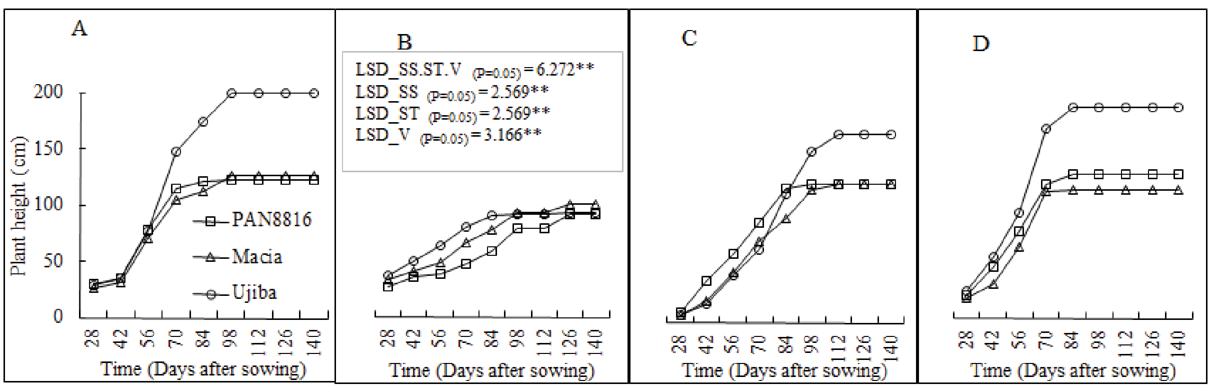

Figure 4.4: Plant height progressions in PAN8816, Macia and Ujiba sorghum varieties planted at Ukulinga (A and C) and Umbumbulu (B and D) during 2013/14 and 2014/15 growing seasons respectively. Note: SS.ST.V refers to the interaction between growing season (SS), planting site (ST) and sorghum varieties (V). SS refers to growing season, ST refers to planting site, while V refers variety. Means were separated by least significant values (LSD) at P= 0.05.

Achieving high canopy cover is important in reducing soil evaporation water losses and improving biomass production via maximizing transpiration (Mabhaudhi et al., 2013). Since transpiration is directly correlated to biomass, a larger canopy will translate to higher biomass and subsequently yield (Mabhaudhi et al., 2013). Canopy cover varied highly significantly ($P<0.001$) between seasons, planting sites and genotypes. Based on means of genotypes across seasons, high CC was observed at Ukulinga (57%) compared to Umbumbulu (32%) (Fig 4.5). This was consistent with low water availability and the stunted plant growth (leaf number and plant height) observed at Umbumbulu relative to Ukulinga. Based on means of genotypes for the two planting sites and seasons, CC was significantly higher ($P<0.001$) during the 2014/15 relative to 2013/14 planting season. This was attributed to conditions (temperature, rainfall and soil water availability) having been more favourable during the 2014/15 relative to the 2013/14 planting season. Canopy cover is a representation of plant canopy size (plant height, leaf number, leaf size and angle to the stem). In this instance, differences in leaf number accounted for differences in CC between seasons and planting sites. Based on means of planting sites and seasons, Macia had the lowest CC (41%) while PAN8816 (46%) and Ujiba (46%) had similar CC. This could be attributed to genotypic differences. PAN8816 is a hybrid and generally showed growth that was more vigorous. Ujiba had the same leaf number, taller plants but similar CC compared to PAN8816, hence it could be argued that Ujiba had smaller leaf size even though measurements of leaf size were not conducted.

Chlorophyll content index was not significantly affected by the interaction of sites, seasons and genotypes. However, CCI varied highly significantly ($P<0.001$) for planting sites and seasons. Chlorophyll content index was similar among genotypes. Mean values of planting sites across genotypes showed that CCI for the two planting seasons were higher at Ukulinga (44 and 51) relative to Umbumbulu (35 and 42) (Fig 4.6). At each planting site, CCI generally increased with time. Chlorophyll content index decreased towards end of the growing season (Fig 4.6), possibly due to leaf senescence. Variations in CCI between planting sites and seasons were consistent with observations that Ukulinga experienced less water stress than Umbumbulu, while 2014/15 was the more favourable season than 2013/14. In general, CCI is sensitive to water stress and will decline under water stress (Kapanigowda et al., 2013).

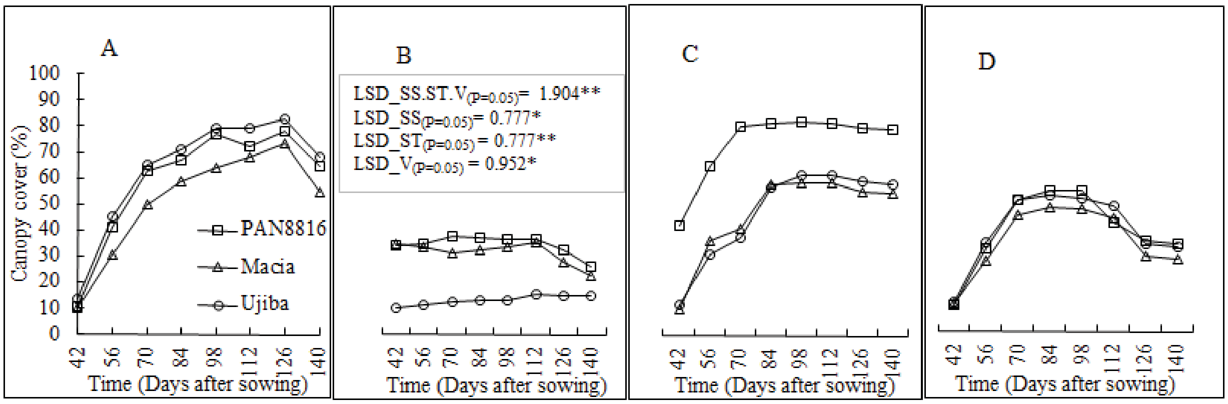

Figure 4.5: Canopy cover in PAN8816, Macia and Ujiba sorghum varieties planted at Ukulinga (A and C) and Umbumbulu (B and D) during 2013/14 and 2014/15 growing seasons respectively. Note: SS.ST.V refers to the interaction between growing season (SS), planting site (ST) and sorghum varieties (V). SS refers to growing season, ST refers to planting site, while V refers variety. Means were separated by least significant values (LSD) at P= 0.05.

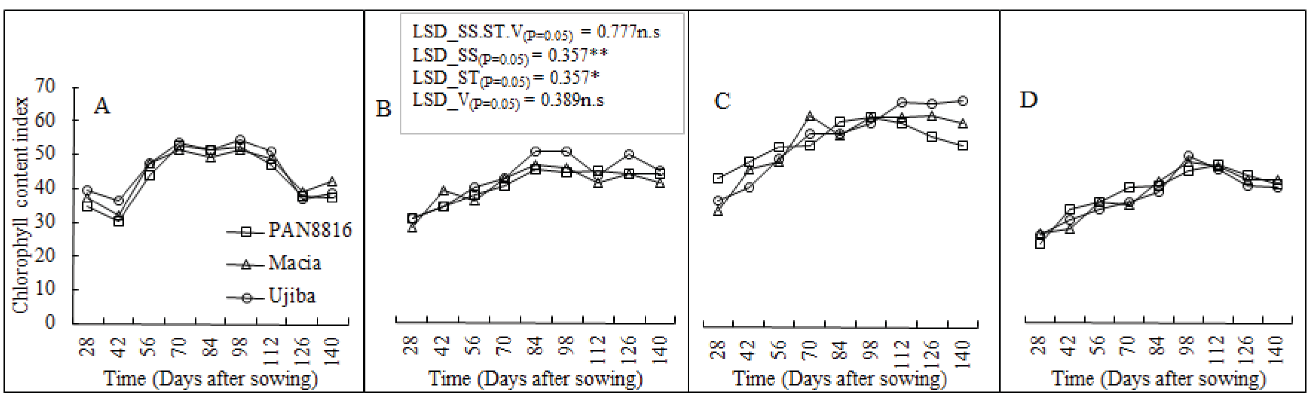

Figure 4.6: Chlorophyll content index in PAN8816, Macia and Ujiba sorghum varieties planted at Ukulinga (A and C) and Umbumbulu (B and D) during 2013/14 and 2014/15 growing seasons respectively. Note: SS.ST.V refers to the interaction between growing season (SS), planting site (ST) and sorghum varieties (V). SS refers to growing season, ST refers to planting site, while V refers variety. Means were separated by least significant values (LSD) at P= 0.05.

Primary response of stomatal opening/ closure is to availability of soil water (Tombesi et al., 2015). Stomatal conductance was recorded only in the 2014/15 season. Results of SC in this study therefore have limited applicability. Sorghum genotypes exhibited statistically similar stomatal conductance across planting sites. However, SC was significantly lower ($P<0.01$) at Umbumbulu (190 mmol m^{-2} s^{-1}) than Ukulinga (292 mmol m^{-2} s^{-1}) (Fig 4.7). Primary response of stomata is to soil water availability. Under water stress, sorghum partially closes stomata to sustain reduced photosynthetic activity. Despite higher rainfall and SC, possibly low PAW due to high clay content and soil water retention in Umbumbulu compared to Ukulinga resulted in lower SC in Umbumbulu. Secondary responses to stomata are controlled by vapour pressure deficit (VPD), which varies according to temperatures, humidity and wind conditions. Fluctuations in weekly observable SC was attributed to variable VPD during measurement days.

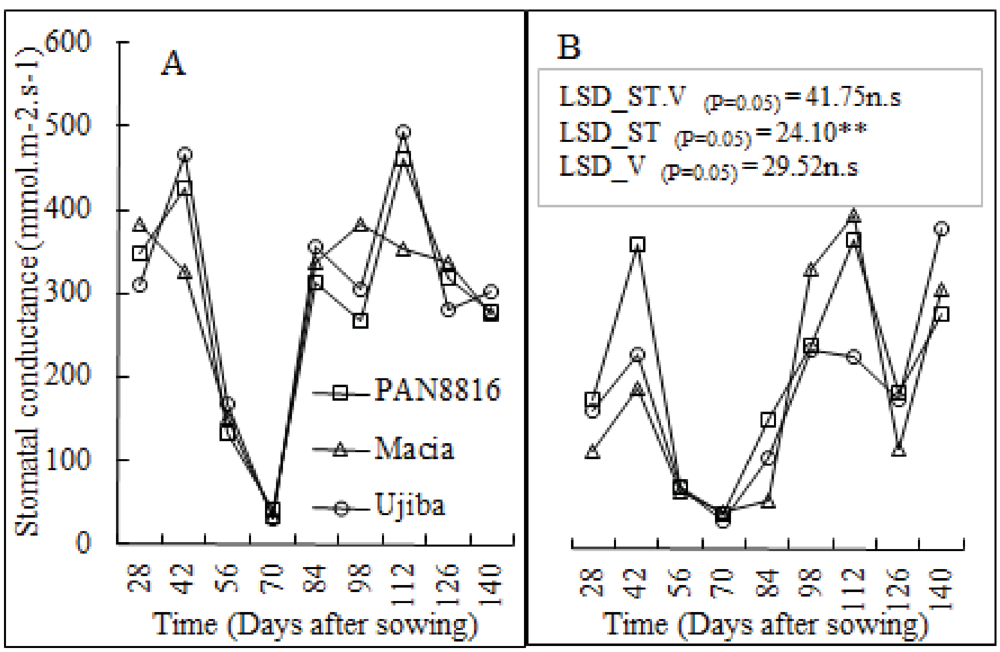

Figure 4.7: Stomatal conductance PAN8816, Macia and Ujiba sorghum varieties planted at Ukulinga (A) and Umbumbulu (B) during 2014/15 growing season. Note: ST.V refers to the interaction between planting site (ST) and sorghum varieties (V). ST refers to planting site, while V refers variety. Means were separated by least significant values (LSD) at P= 0.05.

4.3.3 Crop phenology

Results for phenological development are reported separately for Ukulinga and Umbumbulu, due to non–homogeneity of results (Table 4.3 and 4.4). At Ukulinga, on average, pre–anthesis phenological development occurred earlier for all genotypes during 2013/14 compared to 2014/15 planting season (Table 4.3). This was because 2013/14 planting was associated with less rainfall and low soil water availability, compared to the 2014/15 planting season which could be described as more favourable. Under low soil water availability, crop plants will often exhibit a shorter growth cycle as they try to escape drought (Mabhaudhi and Modi, 2013). Such drought escape and shortened growth cycle is also associated with low leaf number and reduced periods of canopy duration owing to early onset of canopy senescence (Mabhaudhi and Modi, 2013).

Table 4.3: Phenological development of three sorghum genotypes planted at Ukulinga during the first and second season.

		Time taken to reach phenological stage, in days (growing degree days)						
Season	**Genotype**	**Crop establishment**	**End of Juvenile**	**Floral Initiation**	**Flowering**	**Anthesis**	**Start of grain filling**	**Physiological maturity**
First	PAN8816	14.0 (230.7) a	56.0 (883.3) a	63.0 (983.6) a	70.0 (1095.8) a	84.0 (1275.2) a	105.0 (1524.0)	133.0 (1841.7)
	Macia	14.0 (230.7) a	63.0 (983.6) b	70.0 (1095.8) b	77.0 (1194.6) b	91.0 (1360.4) b	112.0 (1609.1)	140.0 (1921.3)
	Ujiba	14.0 (230.7) a	65.3 (1016.0) b	72.3 (1135.9) b	79.3 (1216.3) b	93.3 (1389.5) c	112.0 (1609.1)	133.0 (1841.7)
	Mean	14.0 (230.7)	61.3 (849.6)	67.7 (929.7)	75.3 (1008.8)	89.3 (1157.4)	109.7 (1356.9)	135.3 (1587.6)
Second	PAN8816	14.0 (176.1) a	77.0 (1081.0) c	84.0 (1090.1) c	91.0 (1298.1) c	98.0 (1390.3) d	105.0 (1483.2)	126.0 (1811.2)
	Macia	18.7 (257.9) b	91.0 (1298.0) e	98.0 (1390.3) e	105.0 (1483.2) e	112.0 (1584.4) f	119.0 (1703.6)	140.0 (1999.5)
	Ujiba	28.0 (357.1) c	84.0 (1190.1) d	91.0 (1298.1) d	98.0 (1390.3) d	105.0 (1483.2) e	112.0 (1584.4)	126.0 (1811.2)
	Mean	20.0 (246.7)	81.7 (1154.7)	91.0 (1298.1)	98.0 (1390.3)	105.0 (1483.2)	112.0 (1584.4)	131.3
LSD		3.0	3.0	3.0	3.0	3.0	–	–
CV%		3.9	0.9	0.8	0.7	0.7	0.0	0.0

Note: Values sharing the same letter are similar at LSD = 0.05.

Table 4.4: Phenological development of three sorghum genotypes planted at Umbumbulu during the first and second season.

Season	Genotype	Time taken to reach phenological stage, in days (growing degree days)						
		Crop establishment	**End of Juvenile**	**Floral Initiation**	**Flowering**	**Anthesis**	**Start of grain filling**	**Physiological maturity**
First	PAN8816	14.0 (202.6)	70.0 (1029.4)	70.0 (1029.4)	84.0 (1224.6)	98.0 (1426.5)	112.0 (1592.5)	140.0 (1911.4)
	Macia	14.0 (202.6)	84.0 (1224.6)	84.0 (1224.6)	98.0 (1426.5)	112.0 (1592.5)	112.0 (1592.5)	140.0 (1911.4)
	Ujiba	14.0 (202.6)	84.0 (1224.6)	84.0 (1224.6)	98.0 (1426.5)	112.0 (1592.5)	112.0 (1592.5)	140.0 (1911.4)
	Mean	14.0 (202.6)	79.3 (1163.4)	79.3 (1163.4)	93.3 (1360.4)	107.3 (1539.5)	112.0 (1592.5)	140.0 (1911.4)
Second	PAN8816	14.0 (134.6)	84.0 (888.1)	84.0 (888.1)	98.0 (1092.2)	112.0 (1297)	126.0 (1501.2)	140.0 (1696.4)
	Macia	14.0 (134.6)	84.0 (888.1)	84.0 (888.1)	98.0 (1092.2)	112.0 (1297)	126.0 (1501.2)	140.0 (1696.4)
	Ujiba	14.0 (134.6)	84.0 (888.1)	84.0 (888.1)	98.0 (1092.2)	112.0 (1297)	126.0 (1501.2)	140.0 (1696.4)
	Mean	14.0 (134.6)	84.0 (888.1)	84.0 (888.1)	98.0 (1092.2)	112.0 (1297)	126.0 (1501.2)	140.0 (1696.4)
LSD		–	-	–	–	–	–	–
CV%		0.0	0.0	0.0	0.0	0.0	0.0	0.0

In exchange for this, post-anthesis development and physiological maturity were delayed in all genotypes in the first compared to the second season (Table 4.3). Low, irregular rainfall, and a consistent decrease in soil water content (Fig 4.2) potentially resulted in increased water stress. Sorghum utilises quiescence adaptive mechanisms to allow for extreme drought tolerance (Dugas et al., 2011), remaining dormant during drought conditions and only resuming growth once conditions are deemed favourable (Assefa et al., 2010). This is an important plant adaptation mechanism that ensures crop survival and yield under transient stress thus almost assuring farmers of ‘some’ yield even under adverse conditions when other crops would fail. This could explain post–anthesis delays in time to reaching physiological maturity as a response to irregular and low rainfall. Despite early pre-anthesis development in PAN8816 compared to Ujiba, they both reached physiological maturity at similar times (133 DAS for first season, and 126 DAS during the second season), resulting in shorter grain filling period in Ujiba. Longer grain filling period can allow for increases in yield (Richards, 2000). Shorter grain filling period assures the crop of ‘some’ yield under water stress. Physiological maturity was latest in Macia; this led to extended grain filling period similar to that of PAN8816. Ujiba, however, hastened grain filling under water scarcity. Sorghum phenology was hastened in Ujiba and PAN8816 under low soil water availability. Macia delayed phenological development and matured relatively later than the other two genotypes. Macia and PAN8816 genotypes demonstrated dormancy in terms of delaying grain filling until conditions favourable were restored.

At Umbumbulu, all genotypes established 14 DAS during both planting seasons. Pre–anthesis development occurred earlier in PAN8816 compared to Ujiba and Macia during the 2013/14 planting season (Table 4.4). However, all genotypes reached physiological maturity at 140 DAS. Phenological development was similar for all genotypes during the 2014/15 planting season. Genotypic responses in dry biomass accumulation (Fig 4.8) and final biomass (Table 4.2) were not statistically different, also resulting in insignificant variations with respect to the interaction of planting sites, seasons and genotypes. Sorghum has exceptional drought tolerance (i.e. ability to maintain high tissue water status) which would have allowed for reduced but maintained photosynthesis under water stress (Blum, 2005). All sorghum genotypes reduced leaf, number, CCI and SC in response to low water availability in Umbumbulu. Umbumbulu dry biomass accumulation and final biomass was significantly lower than Ukulinga as a result, which highlights sorghum’s adaptive mechanisms under conditions of low soil water availability. Its deep rooting which allows for enhanced soil water capture also supports this.

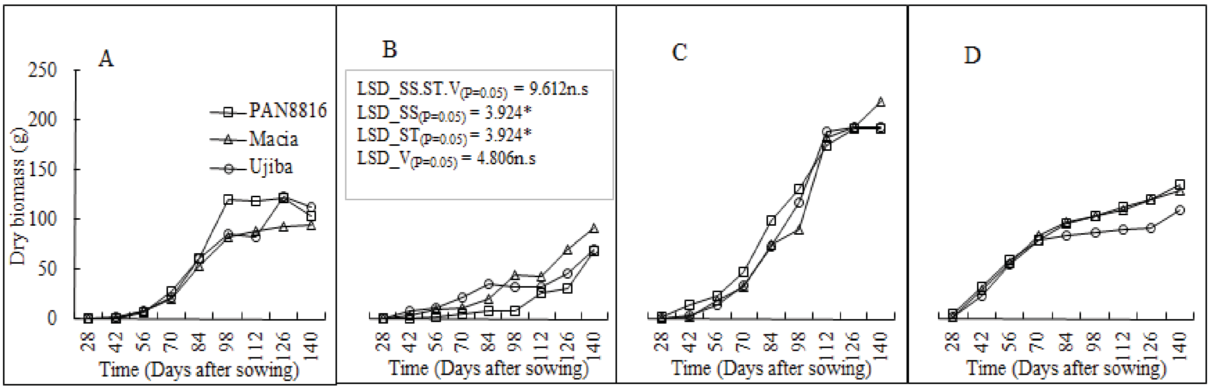

Figure 4.8: Destructively sampled dry aboveground biomass of PAN8816, Macia and Ujiba sorghum varieties planted at Ukulinga (A and C) and Umbumbulu (B and D) during 2013/14 and 2014/15 growing seasons respectively. Note: SS.ST.V refers to the interaction between growing season (SS), planting site (ST) and sorghum varieties (V). SS refers to growing season, ST refers to planting site, while V refers variety. Means were separated by least significant values (LSD) at P= 0.05.

4.3.4 Yield, water use and yield related components

Total panicle yield did not show significant interactions between sites, seasons and genotypes. Panicle yield reduced in response to low water availability, resulting in significantly low panicle yield in Umbumbulu compared to Ukulinga site (Table 4.2). Genotypic differences in panicle yield were statistically insignificant. However, relatively low panicle yield was achieved in Ujiba landrace (2511 kg ha^{-1}) compared to PAN8816 (3004 kg ha^{-1}) and Macia (3516 kg ha^{-1}), which highlights the advantage of breeding attempts in hybrids and open–pollinated varieties. This was attributed to hastened grain filling stage in Ujiba in response to soil plant available water. Macia and PAN8816 appeared to employ tolerance strategies towards post–anthesis water stress, whilst Ujiba employed escape strategies to ensure yield production under water stress.

Sorghum water requirements is normally comprised in the range 450–650 mm (Jewitt et al., 2009). Measured crop water use was below reported water requirements for all seasons, genotypes and planting sites (Table 4.2). This was directly linked to low rainfall (Table 4.2), implying that water was limiting to crop production. Sorghum WUE was reported to be 12.4 – 13.4 kg.ha^{-1}.mm^{-1} in Nebraska under irrigated trials with optimal water use (476 mm) (Maman et al., 2003). In this study, sub-optimal plant water availability resulted in sub–optimal WUE. On the contrary, Abdel-Motagally (2010) found maximal WUE under sub–optimal water availability due to sustained biomass production under significantly low plant available water.

Different genotypes used, duration and extent of water scarcity accounted for disagreement of results in this study with those of Abdel-Motagally (2010). Total and panicle WUE were respectively lower (P<0.05) at Umbumbulu (14.9 and 7.5 $kg.ha^{-1}.mm^{-1}$) relative to Ukulinga (21.5 and 11.0 $kg.ha^{-1}.mm^{-1}$). Macia had higher panicle WUE (10.5 $kg.ha^{-1}.mm^{-1}$) relative to PAN8816 (9.3 $kg.ha^{-1}.mm^{-1}$) and Ujiba (7.9 $kg.ha^{-1}.mm^{-1}$), respectively. Smallholder farmers can afford to continue cultivating Ujiba as the yield disadvantage is minimal under rainfed agriculture.

4.4 Conclusion

Under low soil water availability, sorghum showed adaptation through leaf number, CCI, SC, and phenological plasticity. Lack of significant genotypic differences in yield and WUE highlights that all three genotypes are equally suitable for production under sub–optimal conditions. Studies using multiple rain-fed agro–ecologies of SSA are required to conclude on water use, yield and WUE of sorghum genotypes across SSA. Long-term weather data and analysis of rainfall distribution in relation to crop water requirements at different growth stages would be valuable for knowledge of how water availability affects yield and WUE in rainfed sorghum. Due to feasibility constraints, the use of crop models to extrapolate water use and yield potential of sorghum genotypes under rainfed agriculture is imperative.

References

Abdel-Motagally, F.M.F., 2010. Evaluation of water use efficiency under different water regimes in grain sorghum (*Sorghum bicolor*, L. Moench). World J. Agric. Sci. 6, 499–505.

Assefa, Y., Staggenborg, S.A., Prasad, V.P. V, 2010. Grain sorghum water requirement and responses to drought stress: A review. Crop Manag. 9, 1–12.

Blum, A., 2005. Drought resistance, water-use efficiency, and yield potential—are they compatible, dissonant, or mutually exclusive? Aust. J. Agric. Res. 56, 1159–1168.

Brauman, K., Siebert, S., Foley, J., 2013. Improvements in crop water productivity increase water sustainability and food security—a global analysis. Environ. Res. Lett. 8, 1–8.

Charyulu, C.D., Bantilan, M.C.S., Reddy, B. V, Kumar, A.A., Ahmed, I., Davis, J., 2014. Estimation of ICRISAT Sorghum Research Spillover benefits – Strategies for Research Prioritization and Resource Allocation. Patancheru.

Dugas, D. V, Monaco, M.K., Olson, A., Klein, R.R., Kumari, S., Ware, D., Klein, P.E., 2011. Functional annotation of the transcriptome of *Sorghum bicolor* in response to osmotic stress and abscisic acid. BMC Genomics 12, 514.

Du Plesis, J., 2008. Sorghum production. Department of Agriculture: Republic of South Africa, and Agricultural Research Council.

Food and Agriculture Organization Statistics (FAOSTAT), 2013. FAO statistical yearbook 2013. World food and agriculture. Rome, Italy. http://faostat.fao.org/site/339/default.aspx (accessed on October 10, 2015).

Farooq, M., Wahid, A., Kobayashi, N., Fujita, S.M.A., 2009. Plant drought stress: effects, mechanisms and management. Agron. Sustain. Dev. 29, 185–212.

Giovannucci, D., Scherr, S., Nierenberg, D., Hebebrand, C., Shapiro, Milder, J., & Wheeler, K., 2012. Food and Agriculture: The future of sustainability Food and Agriculture: The future of sustainability.

Hattori, T., Inanaga, S., Araki, H., An, P., Morita, S., Luxová, M., Lux, A., 2005. Application of silicon enhanced drought tolerance in *Sorghum bicolor*. Physiol. Plant. 123, 459–466.

Hsiao, T.C., Xu, L.-K., 2000. Sensitivity of growth of roots versus leaves to water stress: biophysical analysis and relation to water transport. J. Exp. Bot. 51, 1595–1616.

Kapanigowda, M.H., Perumal, R., Djanaguiraman, M., Aiken, R.M., Tesso, T., Prasad, P.V., Little, C.R., 2013. Genotypic variation in sorghum [*Sorghum bicolor* (L.) Moench] exotic germplasm collections for drought and disease tolerance. Springerplus 2, http://www.springerplus.com/content/2/1/650.

Mabhaudhi, T., 2012. Drought tolerance and water use of selected South African landraces (*Colocasia esculenta* L. Schott) and bambara groundnut (*Vigna subterranea* L. Verdc). University of KwaZulu-Natal.

Mabhaudhi, T., Modi, A. T., 2013. Growth, phenological and yield responses of a bambara groundnut (*Vigna subterranea* (L.) Verdc.) landrace to imposed water stress under field conditions. South African J. Plant Soil 30, 69–79.

Mabhaudhi, T., Modi, A. T., Beletse, Y.G., 2013. Growth, phenological and yield responses of a bambara groundnut (*Vigna subterranea* L. Verdc) landrace to imposed water stress: IL. Rain shelter conditions. Water SA 39, 191–198.

Mabhaudhi, T., Modi, A.T., Beletse, Y.G., 2014. Parameterisation and evaluation of the FAO-AquaCrop model for a South African taro (*Colocasia esculenta* L. Schott) landrace. Agric. For. Meteorol. 192–193, 132–139.

Maman, N., Lyon, D.J., Mason, S., Galusha, T.D., Higgins, R., 2003. Pearl millet and grain sorghum yield response to water supply in Nebraska. Agron. J. 95, 1618–1624.

McMaster, G.S., Wilhelm, W.W., 1997. Growing degree-days: one equation, two interpretations. Agric. For. Meteorol. 87, 291–300.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: Between optimism and caution. Agric. Water Manag. 97, 528–535.

Murray, S.J., Foster, P.N., Prentice, I.C., 2012. Future global water resources with respect to climate change and water withdrawals as estimated by a dynamic global vegetation model. J. Hydrol. 448–449, 14–29.

Postel, S.L., 2003. Securing water for people, crops, and ecosystems: New mindset and new priorities. Nat. Resour. Forum 27, 89–98.

Promkhambut, A., Polthanee, A., Akkasaeng, C., Younger, A., 2011. Growth, yield and aerenchyma formation of sweet and multipurpose sorghum (*Sorghum bicolor* L. Moench) as affected by flooding at different growth stages. Aust. J. Crop Sci. 5, 954–965.

Richards, R.A., 2000. Selectable traits to increase crop photosynthesis and yield of grain crops. J. Exp. Bot. 51, 447–458.

Ridolfi, L., D'Odorico, P., Laio, F., Tamea, S., Rodriguez-Iturbe, I., 2008. Coupled stochastic dynamics of water table and soil moisture in bare soil conditions. Water Resour. Res. 44, 1–11.

Ringler, C., Zhu, T., Cai, X., Koo, J., Wang, D., 2010. Climate change impacts on food security in Sub-Saharan Africa insights from comprehensive climate change scenarios, Food Policy. Discussion Paper. International Food Policy Institute (IFPI).

Rosegrant, M.W., Ringler, C., Zhu. T., 2009. Water for agriculture: maintaining foods under growing scarcity. Annu. Rev. Environ. Resour. 34, 205–222.

Rosenow, D.T., and J.A. Dahlberg. 2000. Collection, conversion and utilisation of sorghum, in: Smith, C.W., Frederiksen, R.A. (Eds), Sorghum – Origin, History, Technology and Production. John Wiley and Sons, New York. pp. 309–328.

Silva, C., Ferreira, A., Gonzaga, W., Galon, L., Petter, F.A., May, A., Karam, D., 2014. Weed interference in the sweet sorghum crop. Bragantia, Campinas 73, 438–445.

Singh, P., S.P. Wani, P. Pathak, K.L. Sahrawat, and A.K. Singh. 2011. Increasing crop productivity and effective use of water in rainfed agriculture. In: Integrated watershed management in rainfed agriculture. CRC Press, London. pp. 315–347.

Staggenborg, S.A., Dhuyvetter, K.C., Gordon, W.B., 2008. Grain sorghum and corn comparisons: Yield, economic, and environmental responses. Agron. J. 100, 1600–1604.

Takele, A., Farrant, J., 2013. Water relations, gas exchange characteristics and water use efficiency in maize and sorghum after exposure to and recovery from pre and post-flowering dehydration. African J. Agric. Res. 8, 6468–6478.

Tombesi, S., Nardini, A., Frioni, T., Soccolini, M., Zadra, C., Farinelli, D., Poni, S., Palliotti, A., 2015. Stomatal closure is induced by hydraulic signals and maintained by ABA in drought-stressed grapevine. Sci. Rep. 5, DOI: 10.1038/srep12449.

Tres, P.D.E., Arbóreas, E., Especies, D.E.T., Caducifolias, A., 2010. Effect of water stress on growth and water use efficiency of tree seedlings. J. Taibah Univ. Sci. 3, 39–48.

Whitmore, A.P., Whalley, W.R., 2009. Physical effects of soil drying on roots and crop growth. J. Exp. Bot. 60, 2845–2857.

Xu, Z., Zhou, G., Shimizu, H., 2010. Plant responses to drought and rewatering. Plant Signal. Behav. 5, 649–654.

Zhao, C., Feng, Z., Chen, G., 2004. Soil water balance simulation of alfalfa (*Medicago sativa* L.) in the semiarid Chinese Loess Plateau. Agric. Water Manag. 69, 101–114.

CHAPTER 5

YIELD, WATER USE AND PRODUCTIVITY OF SELECTED GRAIN LEGUMES IN A SEMI-ARID ENVIRONMENT

Chibarabada, T.P., Modi, A.T. and Mabhaudhi, T.

5.1 Introduction

Grain legumes play an integral role in the 2030 agenda for sustainable development due to their high nutritional value and various environmental and sustainability benefits (FAO, 2016). Their promotion could alleviate the high prevalence of malnutrition reported in regions such as sub-Saharan African and South Asia where 23.2% and 34.5% of the population, respectively, is malnourished (FAO, IFAD and WFP, 2015). In addition to the existing burden of malnutrition, these regions are expected to carry more than 70% of the world's expected 2 billion population growth by 2050 (Population Reference Bureau, 2014).

Sub-Saharan African and South Asia are also faced with increasing aridity and water scarcity, which hinders agricultural production (Falkenmark et al., 1989; Seckler et al., 1999; Rijsberman, 2006). Current strategies on increasing food production under water limited conditions emanate from the 'more crop per drop' notion which describes the need to produce more food with the current water resources or using less water for the current food production (Passioura, 2006; Zoebl, 2006; Molden et al., 2010). This has also been referred to as 'improving water productivity'. The greatest improvements in water productivity (WP) under water scarce regions will derive from better agronomic practices, improved irrigation management and growing appropriate crops and genotypes (Passioura, 2006; Molden et al., 2010; Karrou and Oweis, 2012; Descheemaeker et al., 2013; Estrada et al., 2015).

Currently the major grain legumes dominating cropping systems in SSA and SA are soybean, groundnut and dry bean (Chibarabada et al., 2017). According to Pasquet (1999), these major crops have replaced underutilised and traditional grain legumes in rural cropping systems. Several authors have proposed re-introducing traditional crops into cropping systems as they are well adapted to water limiting conditions (Ebert, 2014; Chivenge et al., 2015; Massawe et al., 2015; Mayes et al., 2011; Nyadanu and Lowor, 2015). They have the potential to contribute to the increasing food needs (Ebert, 2014; Chivenge et al., 2015; Massawe et al., 2015; Mayes et al., 2011; Nyadanu and Lowor, 2015). There have been separate studies on determining yield, water use and water use efficiency of grain legumes under different environments (Abayomi et al., 2008; Mabhaudhi et al., 2013; Munoz-Perea et al., 2007; Obalum et al., 2011; Patel et al., 2008). Results have been inconclusive and have not made any significant impact to science because they were wide ranging. This is because water use and water use efficiency values differ across environment and management practices (Allandale et al., 2012). There is need for studies to provide a comparison of major legumes and traditional legumes in order to benchmark traditional grain legumes to major grain legumes. This study seeks to make a comparative of yield, water use and water productivity of selected indigenous grain legumes [bambara groundnut (*Vigna subterranea)* and cowpea *(Vigna unguiculata)*] and selected major grain legumes [dry bean (*Phaseolus vulgaris*) and groundnut (*Arachis hypogaea)*] under rain-fed, full irrigation and deficit irrigation conditions in a semi-arid environment.

5.2 Material and Methods

5.2.1 Site, climate and soil

Experiments were conducted during the 2015/16 summer season at the University of KwaZulu-Natal's (UKZN) Ukulinga Research Farm in Pietermaritzburg, KwaZulu-Natal (29°37'S; 30°16'E; ALT). Ukulinga is classified as a subtropical climate with low risk of frost occurrence. Average annual rainfall is 694 mm, which is received mainly during the summer months (mid-October to mid-February). Winter rain (April to August) is below 75 mm hence summer is the predominant cropping season under rain-fed conditions. During the summer months, average maximum temperatures are between 26°C and 28°C while minimum temperatures can be as low as 10°C.

The soil profile was characterised by a yellow red soil with an effective rooting depth of 0.40 m. Soil samples were taken to the Department of Agriculture and Rural Development Fertilizer Advisory Service for analyses of nutrients, clay content and pH. Physical characteristics were obtained from Mabhaudhi et al. (2014) who used the same field (Table 5.1).

Table 5.1: Selected soil physical, chemical and textural characteristics at the experimental site.

Soil texture	^{a}BD	pH	Clay	^{b}Sat	^{c}FC	^{d}PWP	^{e}Ksat	^{f}TAW
Clay	g cm^{-3}	(KCl)	% Volumetric				mm day^{-1}	mm
loam	1.47	5.17	37	48.1	40.6	21	25	78.4

^{a}BD = Bulk density; ^{b}Sat = Saturation; ^{c}FC = Field capacity; ^{d}PWP = Permanent wilting point; ^{e}Ksat = Saturated hydraulic conductivity; ^{f}TAW = Total available water.

5.2.2 Plant material, experimental design and management practices

Major grain legumes were defined as those species that are recognized internationally regardless of their centres of diversity, occupy significant crop area, and have been subject to formal crop improvement (Chibarabada et al., 2017). Major grain legumes selected for the study were groundnut and dry bean. Groundnut variety Kwarts was sourced from Agricultural Research Council-Grain Crops Institute, Potchefstroom. Dry bean variety Ukulinga was sourced from McDonald seeds, Pietermaritzburg. Underutilised traditional grain legumes were defined as those that are have originated from the semi and arid tropics (SA and SSA), are neglected or underutilised in any dimension (geographic, social, and economic) (Padulosi et al., 2002). The selected underutilised traditional grain legumes were cowpea and bambara groundnut. Cowpea variety mixed brown was sourced from Capstone seeds, Mooi River. bambara groundnut landrace was sourced from Jozini.

The experimental design was a split-plot design arranged in randomised complete blocks with three replications. The main plots were water regimes (full irrigation, deficit irrigation and rainfed) while the subplots were the four grain legume crops (dry bean, groundnut, cowpea and bambara groundnut). Subplot size was 5 m × 3.75 m. Irrigation was applied through a sprinkler system with a distribution uniformity of 85%. The sprinkler nozzles had a throw distance (radius) of 8 m. The distance between the water treatments was 12 m to avoid sprinkler overspray. Management allowable depletion (MAD) in the full irrigation treatment was 80% of Total Available Water (TAW). The approach to deficit irrigation was to apply irrigation (MAD: 80% TAW) at the growth stages that were most sensitive to water stress (Geerts and Raes 2009). The most water stress sensitive growth stages of the grain legume crop species were the flowering and pod-filling stages (Ahmed and Suliman, 2010; Vurayai et al., 2011). All the water treatments were fully irrigated up to 90% emergence to ensure establishment of all trials. For the rainfed trial, irrigation was withdrawn thereafter and the trial relied entirely on rainfall thereon.

Plant population was 66 666 plants per hectare for bambara groundnut and 88 888 plants per hectare for dry bean and groundnut. The trial was planted on the 17th of November 2016 on ploughed and rotovated land. Groundnut and dry bean were planted on furrows while bambara groundnut was planted on mounted ridges. Groundnut was ridged at four weeks after planting. Seeds were treated with an insecticide (Chlorpyrifos at the rate of 0.6 g of a.i /kg of seed) and a fungicide (Mancozeb at the rate of 0.0015 g a.i per ml per 1 kg of seed) before planting. Based on results of soil analyses, an organic fertiliser, Gromor accelerator (0.3% N, 0.15% P and 0.15% K), was applied at planting at a rate of 4000 kg ha^{-1} to meet the nutrient requirements for the grain legume crops. The trials were kept weed free through routine hand weeding using hand hoes. During weeding, bambara groundnut and groundnut were re-ridged to maintain the ridges. Kemprin (0.15 ml/15 litres water) was sprayed eight weeks after planting to control cutworm and leafhopper. Chlorpyrifos (30 ml/15 litres water) was applied nine weeks after planting to control black aphids.

5.2.3 Measurements

5.2.3.1 Climate data

Daily weather data [maximum (Tmax) and minimum (Tmin) air temperature (°C), rainfall (mm) and reference evapotranspiration (ET_o) (mm)] were obtained from an AWS located at the Research Farm. The AWS is part of the Agricultural Research Council – Institute for Soil, Climate and Water (ARC–ISCW) network of automatic weather stations.

5.2.3.2 Irrigation

The sprinkler irrigation system had an approximate application rate of 7 mm per hour. This was used to estimate irrigation run time. The actual amount of irrigation after each irrigation event was measured using rain gauges randomly placed in the experimental plots.

5.2.3.3 Soil water content

Changes in soil water content (SWC) were measured using a PR2/6 profile probe connected to an HH2 handheld moisture meter (Delta–T, UK). The soil profile at the experiment site was shallow with an effective rooting depth of 0.40 m. The sensors of the PR2/6 profile probe are positioned to measure volumetric water content at six depths (0.10, 0.20, 0.30, 0.40, 0.60 and 1.00 m along the probe). Sensors used in the analysis of SWC where the first four (0.10 – 0.40).

5.2.3.4 Determination of phenological events

Timing of key phenological events (emergence, flowering, podding, senescence and maturity) was done through visual observations. Time to emergence was when 90% of the experimental plants had the coleoptile piecing through the soil. Time to flowering, podding, senescence and maturity was defined by 50% of the experimental plants showing visual signs. A plant was defined to be flowering when the flower fully opens. A plant was defined as podding when the first pod appears on the plant. Senescence was defined when at least 10% of leaves had senesced without new leaves being formed to replace them. A plant matured when at least 50% of leaves had senesced.

5.2.3.5 Yield and yield components

Yield of cowpea was lost to monkeys that are part of the Bisley Valley Nature reserve that is situated next to Ukulinga Research Farm. At harvest, six representative plants of each subplot were harvested. Thereafter the plants were air dried in a controlled environment situated at the UKZN Phytosanitary Unit for 11 days until there were no changes in total biomass observed. Thereafter yield components were determined (total biomass, pod number, pod mass, grain number and grain mass). In the case of dry bean, total biomass referred to the above ground biomass while for groundnut and bambara groundnut total biomass referred to the below and aboveground biomass. Thereafter, harvest index (HI) was determined as:

$$HI = Y_g/B \qquad \text{Equation 5.1}$$

where: HI = harvest index (%), Y_g = economic yield based on grain yield (kg), and B = total biomass (groundnut and bambara groundnut)/ above ground biomass (dry bean) (kg).

5.2.3.6 Determination of water use

Water use (WU) for each treatment was calculated as the residual of a soil water balance (Allen et al., 1998):

$$WU = P + I - D - R - \Delta SWC \qquad \text{Equation 5.2}$$

where: WU = water use = evapotranspiration (mm),

R = rainfall (mm),

I = irrigation (mm),

D = drainage (mm),

R = runoff (mm), and

ΔSWC = changes in soil water content (mm).

Drainage was considered as negligible since the observed impeding layer at 0.4 m restricted downward movement of water beyond the root zone. Runoff (R) was not quantified directly; however, the United States Department of Agriculture - Soil Conservation Service (USDA-SCS) procedure (USDA-SCS, 1967) was used to estimate the monthly effective rainfall that is stored in the root zone after subtracting the amount of rainfall lost to sub-surface runoff. Monthly effective rainfall was estimated using mean monthly rainfall obtained from 30-year rainfall data of Ukulinga Research Station and monthly crop evapotranspiration for the different crops estimated using the crop coefficient approach ETo*Kc (Allen et al., 1998). Net depth of irrigation used was 32 mm. The soil water balance was therefore simplified to;

$$WU = ER + I - \Delta SWC \quad \text{Equation 5.3}$$

where: WU = water use = evapotranspiration (mm),

ER = effective rainfall (mm),

I = irrigation (mm), and

ΔSWC = changes in soil water content (mm).

5.2.3.7 Determination of water productivity

Water Productivity was then calculated as;

$$WP = Ya / ETa \quad \text{Equation 5.4}$$

where: WP is water productivity (kg m^{-3}), Ya is the grain yield (kg) and ETa is the actual evapotranspiration (m^3).

5.2.4 Data analyses

Analysis of variance (ANOVA) was performed using GenStat® 18^{th} Edition (VSN International, UK) at a probability level of 0.05.

5.3 Results

5.3.1 Weather data and irrigation

During the growing season, average maximum and minimum temperatures were 28°C and 16°C respectively. Maximum temperatures ranged between 17°C and 41°C with the highest (41°C) being observed 37 days after planting. Minimum temperatures ranged between 10°C and 21°C (Figure 5.1). The observed temperatures were ideal for production of tropical legumes (Whiteman, 1968; Littleton et al., 1981). Total rainfall and ET_o during the season were 445 mm and 516 mm, respectively (Figure 5.2), implying a deficit of 71 mm. Two rainfall events of approximately 60 mm each were observed at 68 and 120 days after planting. Reference evapotranspiration ranged between 0.59 to 6.85 mm, with an average of 3.6 mm during the season (Figure 5.2). Total supplementary irrigation added to the full irrigation and deficit irrigation trials was 101 mm and 40 mm, respectively, while only 18 mm supplementary irrigation was added to the rainfed trial to support emergence. Based on the USDA-SCS estimations, effective rainfall for the growing months (November to April) was between 50 and 72% of the mean monthly rainfall (Table 5.2).

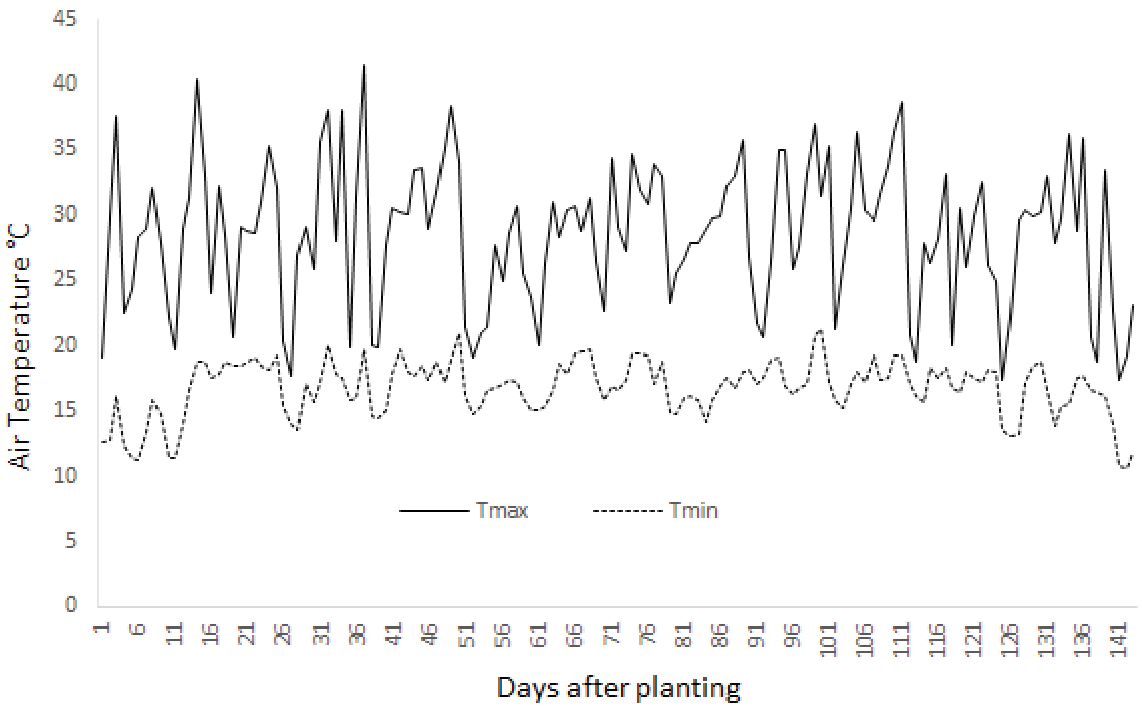

Figure 5.1: Maximum and minimum temperatures (°C) observed at Ukulinga Research Station during the growing period 17 November 2015 to 8 April 2016.

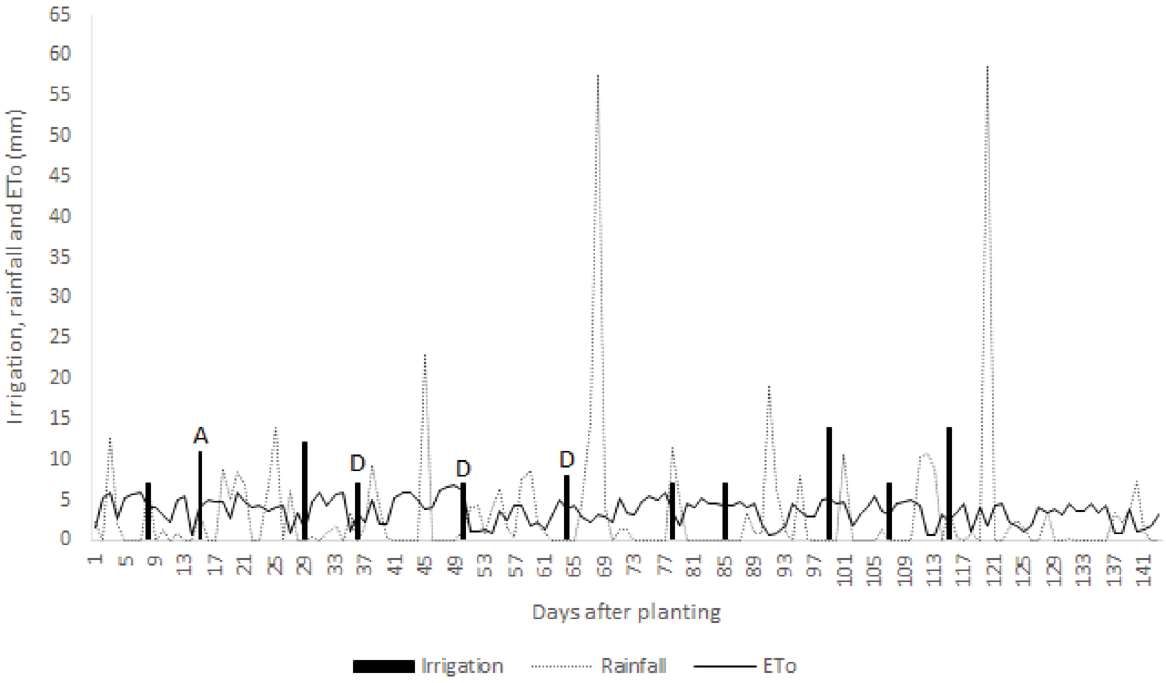

Figure 5.2: Rainfall, ET_o and irrigation applied during growing period 17 November 2015 to 8 April 2016. A = Irrigation applied to all the water treatments (fully irrigated, deficit and rainfed). D = Irrigation applied to the fully irrigated trial together with deficit irrigated trial.

Table 5.2: Monthly effective rainfall (mm) for the different grain legume crops (dry bean, bambara groundnut and groundnut) during the months November to April.

	November	December	January	February	March	April
	mm					
Dry bean	41	72	66	34	66	-
Bambara groundnut	42	73	67	50	53	27
Groundnut	42	73	67	50	53	27

5.3.2 Changes in soil water content

Results of changes in soil water content showed that at planting the profile was below PWP (≈ 60 mm) and went up to above PWP (53% of TAW) two weeks after planting (Figure 5.3). Thereafter soil water content fluctuated between 30 and 90% of TAW for the duration of the experiment. For bambara groundnut soil water content went slightly above FC (Figure 5.3). This could be because of the ridges that improved soil water holding capacity. With respect to the water treatments, there was no clear pattern but it was observed that while all the water treatments had soil water content above PWP, the irrigated and deficit trials had more soil water compared to the rainfed trial (Figure 5.3).

5.3.3 Timing of phenological events

Time to all key phenological events measured during the study (time to emergence, time to flowering, duration of flowering, time to podding, time to senescence and time to maturity) showed significant differences ($P < 0.001$) among the grain legume crops (Table 5.3). Dry bean and groundnut emerged by the ninth day after planting (DAP) while bambara groundnut emerged 16 days after planting. Groundnut was the first to flower and pod (28 and 39 DAP, respectively) while bambara groundnut started flowering and podding (67 and 77 DAP, respectively) (Table 5.3). With respect to time to maturity dry bean matured earlier (104 DAP) than groundnuts and bambara groundnuts that matured 143 DAP. Timing to key phenological events was not affected by water regimes ($P > 0.05$). This was except for time to flowering that showed significant differences ($P < 0.05$) with respect to water regimes. The interaction between the crops and water regimes showed significant differences ($P < 0.05$) with respect to time to flowering, time to podding, time to senescence and time to maturity (Table 5.3). Time to emergence and duration of flowering did not show any significant differences ($P > 0.05$).

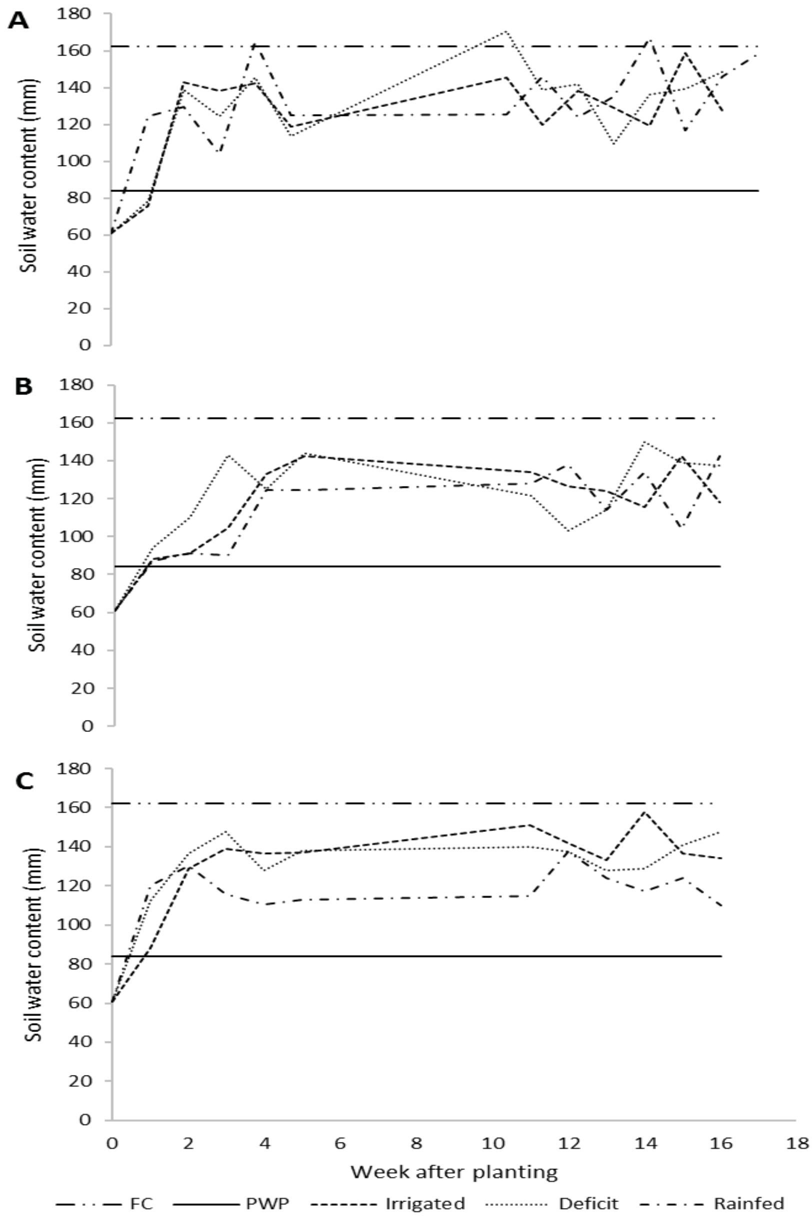

Figure 5.3: Changes in soil water content (mm) for the four grain legumes crops (A = bambara groundnut; B = dry bean; C = groundnut) observed during growing period 17 November 2015 to 8 April 2016.

Table 5.3: Timing of key phenological events of three grain legume crops (dry bean, groundnut and bambara groundnut) grown under three watering regimes (full irrigation, deficit irrigation and rainfed).

		aTTE	bTTF	cDOF	dTTP	eTTS	fTTM
		Days					
Full Irrigation	Dry bean	8	49	14	54	82	104
	Groundnut	9	28	30	39	125	143
	Bambara groundnut	16	67	25	77	119	143
	Mean	12	48	23	56	109	131
Deficit Irrigation	Dry bean	8	49	14	56	93	109
	Groundnut	9	28	23	42	102	143
	Bambara groundnut	16	60	23	42	125	143
	Mean	12	45	20	56	112	131
Rainfed	Dry bean	8	35	15	49	86	100
	Groundnut	9	28	23	42	120	141
	Bambara groundnut	16	63	23	79	123	143
	Mean	12	42	20	56	109	128
Significance	Crops	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Water regime	*ns	0.009	*ns	*ns	*ns	*ns
	Crop*Water regime	*ns	<0.001	*ns	0.019	0.011	0.015

aTTE = Time to emergence; bTTF = Time to flowering; cDOF= Duration of flowering; dTTP = Time to podding; eTTS = Time to senescence; fTTM = Time to maturity; *ns = not significant at P = 0.05.

5.3.4 Yield components, water use and water productivity

Similar to timing of phenological events, results of yield components (total biomass, pod number, pod mass, grain number, grain mass, harvest index) and water productivity showed highly significant differences ($P < 0.001$) among the crop species (Table 5.4). No traits showed any significance difference among the water treatments ($P > 0.05$). The interaction between the crops and the water regimes were only significantly different ($P < 0.05$) for pod mass, grain mass and water productivity (Table 5.4).

Total biomass was highest for groundnuts under deficit irrigation (10.54 tonnes ha^{-1}). The lowest total biomass (4.22 tonnes ha^{-1}) was observed in dry bean under deficit irrigation. Groundnuts produced more pods per plant (> 53), while dry bean produced 18 – 23 pods per plant (Table 5.4). With respect to pod yield, the major grain legumes were superior compared to bambara groundnut. Groundnut had the highest pod yield (3.46 – 4.95 tonnes ha^{-1}) while the lowest pod yield was observed in bambara groundnut (1.65 – 2.20 tonnes ha^{-1}). Grain number and grain mass were also highest in groundnut (106 and 2.90 tonnes ha^{-1}, respectively) under deficit irrigation (Table 5.4). This was followed by dry bean yielding 64 grains per plant, translating it to 2.26 tonnes of grain per hectare. With respect to harvest index, the dynamics changed with dry bean exhibiting a harvest index that was ≈ 45 – 50% higher than that of groundnut and bambara groundnut. The highest harvest index (43%) was observed in dry bean under fully irrigated conditions while the lowest harvest index (21%) was observed for bambara groundnut under rainfed conditions (Table 5.4).

With respect to water use, it was observed that across the water treatments groundnut was the highest water user using 319, 292 and 283 mm under fully irrigated, deficit irrigation and rainfed conditions respectively (Table 5.4). Dry bean was the lowest water using 268, 238 and 238 mm of water under fully irrigated, deficit irrigation and rainfed conditions respectively. Overall results of water productivity showed that groundnut was the most productive, producing 0.61 – 0.99 kg of grain per m^{-3} of water consumed. Bambara groundnut was the least productive, producing 0.39 – 0.53 kg of grain per m^{-3} of water consumed (Table 5.4). Mean numbers of water treatments showed that water productivity improved by ≈ 12% under rainfed and deficit irrigation conditions compared to the fully irrigated conditions.

Table 5.4: Yield and yield parameters (total biomass, pod number, pod mass, grain number, grain mass and harvest index), water use and water productivity of three legume crops (dry bean, groundnut and bambara groundnut) grown under three watering regimes (full irrigation, deficit irrigation and rainfed).

Water treatments	**Crop species**	**Total biomass**	**Pod number**	**Pod mass**	**Grain number**	**Grain mass**	**Harvest index**	**Water use**	**Water Productivity**
		Tonne ha^{-1}	Plant $^{-1}$	Tonne ha^{-1}	Plant $^{-1}$	Tonne ha^{-1}	%	mm	kg m^{-3}
Full Irrigation	Dry bean	5.04	23.5	3.46	64.4	2.26	43.26	268.54	0.84
	Groundnut	8.02	54.6	3.36	77.4	1.95	23.54	319.31	0.61
	Bambara groundnut	6.03	53.1	2.20	45.8	1.48	24.53	317.09	0.47
	Mean	**6.36**	**43.7**	**3**	**62.6**	**1.80**	**30.44**	**301.65**	**0.64**
Deficit Irrigation	Dry bean	4.22	18.9	2.08	40.3	1.40	35.66	238.94	0.62
	Groundnut	10.54	67.1	4.96	106.0	2.90	27.73	292.11	0.99
	Bambara groundnut	6.39	40.2	2.17	45.4	1.41	22.41	263.08	0.53
	Mean	**7.05**	**42.1**	**3.07**	**63.9**	**1.93**	**28.60**	**264.71**	**0.71**
Rainfed	Dry bean	5.28	21.9	2.89	50.2	1.96	37.15	238.50	0.82
	Groundnut	9.65	68.9	4.57	99.9	2.77	28.63	283.01	0.98
	Bambara groundnut	5.00	43.9	1.65	38.3	1.09	21.16	277.00	0.39
	Mean	**6.65**	**44.9**	**3.04**	**62.8**	**1.94**	**28.98**	**266.17**	**0.73**
Significance (P=0.05)	Crops	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001		< 0.001
	Water regime	*ns	*ns	*ns	*ns	*ns	*ns		*ns
	Crops*Water regime	*ns	*ns	0.009	ns	0.031	*ns		0.041

*ns = not significant at P = 0.05.

5.4 Discussion

This study showed that water treatments did not have much influence on results of yield and timing of phenological events. This is contrary to results of several studies that have shown water treatments to significantly affect yield and/or timing of phenological events of grain legumes (Acosta Gallegos and Kohashi Shibata, 1989; Kumaga et al., 2003; Emam et al., 2010; Mabhaudhi et al., 2013; Naresh et al., 2013; Ngwako et al., 2013). Most of these studies were under controlled environment where there is less variation compared to field trials were variables such as rainfall cannot be controlled. Results of soil water content from the current study showed that although soil water content in the rainfed trial was slightly below that of the deficit and fully irrigated trials, soil water content in all the water regimes was above 50% of TAW from the second week after planting until maturity. This implies that the grain crops under study did not undergo any significant water stress, as 50% of TAW was considered readily available to the crops used in the study. This was based on estimated TAW depletion fractions of 45 to 50% where water does not become readily available to legumes crops despite being above permanent wilting point (Allen et al. 1998). The shallow profile depth and good water holding capacity of clay soils, could have also contributed to the high soil water content under all the water regimes.

Plants respond to water stress through various physiological and molecular pathways (Vierling and Kimpel, 1992). This is through various regulatory networks in the plant, which may not be favourable for photosynthesis and plant growth (Vierling and Kimpel, 1992; Osakabe et al., 2014). However, the extent of water stress on yield and yield components also depends on severity and the duration of water stress (Hsiao et al., 1979; Vierling and Kimpel, 1992; Osakabe et al., 2014). Other studies on grain legume species have confirmed these findings, where prolonged duration of water stress affected yield and yield components compared to short-term stress (Kumaga et al., 2003; Muhammad et al., 2016; Shi et al., 2014; Thomas et al. 2004; Vurayai et al., 2011; Withers and Forde, 1979). Under rainfed and deficit irrigated conditions, the grain legumes used during the study could have acclimatised to water limited conditions through physiological and metabolical adjustments hence able to maintain turgor and high leaf water potential. In studies where dry bean (El-Tohamy et al., 2013), castor bean (*Ricinus communis*) (Shi et al., 2014), bambara groundnut (Chibarabada et al., 2015a; Collinson et al., 1997) and groundnut (Bennet et al., 1984) were exposed to long periods of water stress and could adjust osmotically and maintain turgor and high leaf water potential.

The grain legume crops selected for the study performed differently during the study. Other comparative studies on different grain legume crops have also observed crops to differ in their performance (Siddique et al., 2001). Separate water use studies dry bean, groundnut and bambara groundnut observed water use values (318 – 463 mm, 697 – 809, 300 – 638 mm, respectively) (Mabhaudhi et al., 2013; Muñoz-Perea et al., 2007; Patel et al., 2008). Comparing our observed water use and yield values to those observed by separate studies, results show that the latter were higher. Based on results of separate studies, groundnut water use was 60% – 100% more than that of bambara groundnut. This may in part, be some of the reasoning behind that indigenous grain legumes are more adapted to water limited conditions. This does not hold true, based on our findings as bambara groundnut and groundnut have almost similar water values. This highlights the need to make comparative studies under the same environment to have results that are more representative.

With respect to yield and yield components, we observed that the major grain legumes were more yielding compared to bambara groundnut (Table 5.4). Compared to the other crops under study dry bean had a significantly higher harvest index compared to groundnut and bambara groundnut. A high harvest index is an attribute that is favourable as grain is the most economically important part of the plant. Chibarabada et al. (2015b) and Mabhaudhi et al. (2013) have reported poor yields and low harvest index of bambara groundnut. This has been attributed to the use of landraces and lack of high yielding bred varieties among traditional crops.

The highest WP values were observed in groundnut (0.61 – 0.99 kg m^{-3}) and the lowest WP values were observed in bambara groundnut (0.39 – 0.53 kg m^{-3}). This contradicts Chibarabada et al. (2015b) who reported that bambara groundnut was more water use efficient than groundnut. This was based on results of separate studies under different environmental and management conditions, hence maybe misleading. There is dearth of studies on WP of grain legumes. Majority of studies on how grain legumes could convert water into yield have used the water use efficiency parameter, in which values obtained have been inconclusive due to their wide range (Chibarabada et al., 2017).

Although results were not significant ($P > 0.05$), it worth noting that results of water productivity improved by ≈12% under rainfed and deficit irrigated conditions. This supports the recommendations by several authors to apply deficit irrigation to maximise crop water productivity (Fereres and Soriano, 2007; Hirich et al., 2011; Rodrigues and Pereira, 2009; Sarwar and Perry, 2002; Zwart, 2013). This is through reduction of water use but maximisation of yield by ensuring minimum water stress during growth that may adversely affect yield. Our results also confirm that under there is scope to increase food production under rainfed systems through improving water productivity (Descheemaeker et al., 2013; Molden et al., 2010; Zoebl, 2006; Zwart et al., 2010).

5.5 Conclusion

The aim of the study was to compare yield, water use and water productivity of selected major and traditional grain legume species under different irrigation regimes in a semi-arid environment. The irrigation regimes did not show any significant effect on yield, water use and water productivity. The major legumes outperformed bambara groundnut with respect to yield, harvest index and water productivity. The major legumes used in the study were bred varieties while a landrace of bambara groundnut was used. This could be the reason for the inferiority of bambara groundnut. It highlights the need for crop improvement and breeding for yield in traditional grain legumes. The yield, water use and water productivity differences among the grain legume crops emphasizes the importance of growing appropriate crops to improve productivity under rain fed systems. However, decisions should not only be based on yield and water productivity of crops but should also consider the nutritional aspects to address the double burden of hunger and malnutrition.

References

Abayomi, Y.A., Ajibade, T. V, Sammuel, O.F., Saadudeen, B.F., 2008. Growth and yield responses of cowpea (*Vigna unguiculata* (L.) Walp) genotypes to nitrogen fertilizer (NPK) application in the Southern Guinea Savanna zone of Nigeria. Asian J. Plant Sci 7, 170–176.

Acosta Gallegos, J.A., Kohashi Shibata, J., 1989. Effect of water stress on growth and yield of indeterminate dry-bean (*Phaseolus vulgaris*) cultivars. F. Crop. Res. 20, 81–93. doi:10.1016/0378-4290(89)90054-3

Acosta-Gallegos, J.A., Adams, M.W., 1991. Plant traits and yield stability of dry bean (*Phaseolus vulgaris*) cultivars under drought stress. J. Agric. Sci. 117, 213–219.

Acosta-Gallegos, J.A., Quintero, C., Vargas, J., Toro, O., Tohme, J., Cardona, C., 1998. A new variant of arcelin in wild common bean, *Phaseolus vulgaris* L., from southern Mexico. Genet. Resour. Crop Evol. 45, 235–242.

Ahmed, F.E., Suliman, A.S.H., 2010. Effect of water stress applied at different stages of growth on seed yield and water-use efficiency of cowpea. Agric. Biol. J. North Am. 1, 534–540.

Allen, R., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop requirements, Irrigation and Drainage Paper No. 56, FAO. Irrigation and Drainage Paper No. 56, FAO.

Bennet, J.M., Boote, K.J., Hammond, L.C., 1984. Relationships among water potential components, relative water content, and stomatal resistance of field-grown peanut leaves. Peanut Sci 11, 31–35.

Chibarabada, T., Modi, A., Mabhaudhi, T., 2017. Expounding the Value of Grain Legumes in the Semi- and Arid Tropics. Sustainability 9, 60. doi:10.3390/su9010060.

Chibarabada, T.P., Modi, A.T., Mabhaudhi, T., 2015a. Water use characteristics of a bambara groundnut (*Vigna subterranea* L. Verdc) landrace during seedling establishment. Water SA 41, 472–482.

Chibarabada, T.P., Modi, A.T., Mabhaudhi, T., 2015b. Bambara groundnut (*Vigna subterranea*) seed quality in response to water stress on maternal plants. Acta Scandanavia, 65, 364-373.

Chibarabada, T.P., Modi, A.T., Mabhaudhi, T., 2017. Expounding the Value of Grain Legumes in the Semi-arid and Arid Tropics. Sustain. 9, 60. doi:10.3390/su9010060.

Chivenge, P., Mabhaudhi, T., Modi, A.T., Mafongoya, P., 2015. The potential role of neglected and underutilised crop species as future crops under water scarce conditions in Sub-Saharan Africa. Int. J. Environ. Res. Public Health 12, 5685–5711.

Collinson, S.T., Clawson, E.J., Azam-Ali, S.N., Black, C.R., 1997. Effects of soil moisture deficits on the water relations of bambara groundnut (*Vigna subterranea* L. Verde.). J. Exp. Bot. 48, 877–884.

Descheemaeker, K., Bunting, S.W., Bindraban, P., Muthuri, C., Molden, D., Beveridge, M., van Brakel, M., Herrero, M., Clement, F., Boelee, E., 2013. 8 Increasing Water Productivity in Agriculture. Manag. Water Agroecosystems Food Secur. 10, 104.

Ebert, A.W., 2014. Potential of underutilised traditional vegetables and legume crops to contribute to food and nutritional security, income and more sustainable production systems. Sustainability 6, 319–335.

El-Tohamy, W.A., El-Abagy, H.M., Badr, M.A., Gruda, N., 2013. Drought tolerance and water status of bean plants (*Phaseolus vulgaris* L.) as affected by citric acid application. J. Appl. Bot. Food Qual. 86.

Emam, Y., Shekoofa, A., Salehi, F., Jalali, A.H., 2010. Water Stress Effects on Two Common Bean Cultivars with Contrasting Growth Habits. Environ. Sci 9, 495–499.

Estrada, A., Meireles, C., Morales-Castilla, I., Poschlod, P., Vieites, D., Araújo, M.B., Early, R., 2015. Species' intrinsic traits inform their range limitations and vulnerability under environmental change. Glob. Ecol. Biogeogr. 24, 849–858.

Falkenmark, M., Lundqvist, J., Widstrand, C., 1989. Macro-scale water scarcity requires micro-scale approaches, in: Natural Resources Forum. Wiley Online Library, pp. 258–267.

FAO, 2016. Pulses: Nutritious seeds for a sustainable future. doi:978-92-5-109172-2

FAO, IFAD, WFP, 2015. The State of Food Insecurity in the World: Meeting the 2015 international hunger targets: taking stock of uneven progress, FAO, IFAD and WFP. FAO. doi:I4646E/1/05.15

Fereres, E., Soriano, M.A., 2007. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58, 147–59. doi:10.1093/jxb/erl165

Hirich, A., Choukr-allah, R., Jacobsen, S.E., Hamdy, A., 2011. Improving Water Productivity of Chickpea by the Use of Deficit Irrigation with Treated Domestic Wastewater. strategies 3, 5.

Hsiao, T.C., Fereres, E., Acevedo, E., Henderson, D.W., 1976. Water Stress and Dynamics of Growth and Yield of Crop Plants. Springer Berlin Heidelberg, pp. 281–305. doi:10.1007/978-3-642-66429-818.

Karrou, M., Oweis, T., 2012. Water and land productivities of wheat and food legumes with deficit supplemental irrigation in a Mediterranean environment. Agric. water Manag. 107, 94–103.

Kelly, J.D., Kolkman, J.M., Schneider, K., 1998. Breeding for yield in dry bean (*Phaseolus vulgaris* L.). Euphytica 102, 343–356.

Kumaga, F.K., Adiku, S.G.K., Ofori, K., 2003. Effect of Post-flowering Water Stress on Dry Matter and Yield of Three Tropical Grain Legumes. Int. J. Agric. Biol. 5, 405–407.

Littleton, E.J., Dennett, M.D., Elston, J., Monteith, J.L., 1981. The growth and development of cowpeas (*Vigna unguiculata*) under tropical field conditions. J. Agric. Sci. 97, 539–550.

Mabhaudhi, T., Modi, A., Beletse, Y., 2013. Growth, phenological and yield responses of a bambara groundnut (*Vigna subterránea* L. Verdc) landrace to imposed water stress: II. Rain shelter conditions. Water SA 39, 191–198.

Mabhaudhi, T., Modi, A.T., 2013. Growth, phenological and yield responses of a bambara groundnut (*Vigna subterranea* (L.) Verdc.) landrace to imposed water stress under field conditions. South African J. Plant Soil 30, 69–79.

Mabhaudhi, T., Modi, A.T., Beletse, Y.G., 2014. Parameterization and testing of AquaCrop for a South African bambara groundnut landrace. Agron. J. 106, 243–251.

Massawe, F.J., Mayes, S., Cheng, A., Chai, H.H., Cleasby, P., Symonds, R., Ho, W.K., Siise, A., Wong, Q.N., Kendabie, P., 2015. The Potential for Underutilised Crops to Improve Food Security in the Face of Climate Change. Procedia Environ. Sci. 29, 140–141.

Mayes, S., Massawe, F.J., Alderson, P.G., Roberts, J.A., Azam-Ali, S.N., Hermann, M., 2012. The potential for underutilised crops to improve security of food production. J. Exp. Bot. 63, 1075–9. doi:10.1093/jxb/err396

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: between optimism and caution. Agric. Water Manag. 97, 528–535.

Muhammad, Y.Y., Mayes, S., Massawe, F., 2016. Effects of short-term water deficit stress on physiological characteristics of Bambara groundnut (*Vigna subterranea* (L.) Verdc.). South African J. Plant Soil 33, 51–58.

Munoz-Perea, C.G., Allen, R.G., Westermann, D.T., Wright, J.L., Singh, S.P., 2007. Water use efficiency among dry bean landraces and cultivars in drought-stressed and non-stressed environments. Euphytica 155, 393–402.

Naresh, R., Dwivedi, A., Kumar, V., 2013. African Journal of Biochemistry Research Effects of water stress on physiological processes and yield attributes of different mungbean (L.) varieties 7, 55–62. doi:10.5897/AJBR13.0677

Ngwako, S., Balole, T. V, Malambane, G., 2013. The effect of irrigation and planting date on the growth and yield of Bambara groundnut landraces. Int. J. Agric. Crop Sci.

Nyadanu, D., Lowor, S.T., 2015. Promoting competitiveness of neglected and underutilised crop species: comparative analysis of nutritional composition of indigenous and exotic leafy and fruit vegetables in Ghana. Genet. Resour. Crop Evol. 62, 131–140.

Obalum, S.E., Igwe, C.A., Obi, M.E., Wakatsuki, T., 2011. Water use and grain yield response of rainfed soybean to tillage-mulch practices in southeastern Nigeria. Sci. Agric. 68, 554–561.

Olayinka, B.U., Etejere, E.O., 2016. Weed Control Methods Affect Growth, Yield and Economic Returns in Groundnut. Ann. West Univ. Timisoara. Ser. Biol. 19, 17.

Osakabe, Y., Osakabe, K., Shinozaki, K., Tran, L.-S.P., 2014. Response of plants to water stress. Front. Plant Sci. 5, 86. doi:10.3389/fpls.2014.00086.

Padulosi, S., Hodgkin, T., Williams, J.T., Haq, N., Engles, J.M.M., Rao, V.R., Brown, A.H.D., Jackson, M.T., 2002. 30 Underutilised Crops: Trends, Challenges and Opportunities in the 21st Century. CABI New York, USA.

Pasquet, R.S., 1999. Genetic relationships among subspecies of *Vigna unguiculata* (L.) Walp. based on allozyme variation. Theor. Appl. Genet. 98, 1104–1119.

Passioura, J., 2006. Increasing crop productivity when water is scarce—from breeding to field management. Agric. water Manag. 80, 176–196.

Patel, G.N., Patel, P.T., Patel, P.H., 2008. Yield, water use efficiency and moisture extraction pattern of summer.

Population Reference Bureau, 2014. 2014 World Population Data Sheet.

Rijsberman, F.R., 2006. Water scarcity: fact or fiction? Agric. water Manag. 80, 5–22.

Rodrigues, G.C., Pereira, L.S., 2009. Assessing economic impacts of deficit irrigation as related to water productivity and water costs. Biosyst. Eng. 103, 536–551. doi:10.1016/j.biosystemseng.2009.05.002

Sarwar, A., Perry, C., 2002. Increasing water productivity through deficit irrigation: evidence from the Indus plains of Pakistan. Irrig. Drain. 51, 87–92. doi:10.1002/ird.39

Seckler, D., Barker, R., Amarasinghe, U., 1999. Water scarcity in the twenty-first century. Int. J. Water Resour. Dev. 15, 29–42.

Shi, G., Zhu-Ge, F., Liu, Z., Le, L., 2014. Photosynthetic responses and acclimation of two castor bean cultivars to repeated drying–wetting cycles. J. Plant Interact. 9, 783–790.

Siddique, K.H.M., Regan, K.L., Tennant, D., Thomson, B.D., 2001. Water use and water use efficiency of cool season grain legumes in low rainfall Mediterranean-type environments. Eur. J. Agron. 15, 267–280.

Thomas, Robertson, M.J., Fukai, S., Peoples, M.B., 2004. The effect of timing and severity of water deficit on growth, development, yield accumulation and nitrogen fixation of mungbean. F. Crop. Res. 86, 67–80. doi:10.1016/S0378-4290(03)00120-5.

USDA-SCS, 1967. Irrigation water requirements, Technical Release 21.

Vierling, E., Kimpel, J.A., 1992. Plant responses to environmental stress. Curr. Opin. Biotechnol.

3, 164–170. doi:10.1016/0958-1669(92)90147-B.

Vurayai, R., Emongor, V., Moseki, B., 2011. Effect of water stress imposed at different growth and development stages on morphological traits and yield of Bambara Groundnuts (Vigna subterranea L. Verdc). Am. J. Plant Physiol. 6, 17–27.

Whiteman, P.C., 1968. The effects of temperature on the vegetative growth of six tropical legume species. Anim. Prod. Sci. 8, 528–532.

Withers, N.J., Forde, B.J., 1979. Effects of water stress on Lupinus albus: III. Response of seed yield and vegetative growth to water stress imposed during two or three growth stages. New Zeal. J. Agric. Res. 22, 463–474.

Zoebl, D., 2006. Is water productivity a useful concept in agricultural water management? Agric. Water Manag. 84, 265–273.

Zwart, S.J., 2013. 21 Assessing and Improving Water Productivity of Irrigated Rice Systems in Africa. Realiz. Africa's Rice Promise 265.

Zwart, S.J., Bastiaanssen, W.G.M., de Fraiture, C., Molden, D.J., 2010. A global benchmark map of water productivity for rainfed and irrigated wheat. Agric. Water Manag. 97, 1617–1627. doi:10.1016/j.agwat.2010.05.018

CHAPTER 6

WATER USE AND PRODUCTIVITY OF A SORGHUM-COWPEA-BOTTLE GOURD INTERCROP SYSTEM

Chimonyo, V.G.P., Modi, A.T. and Mabhaudhi, T.

6.1 Introduction

Sub-Saharan Africa (SSA) is characterised by both physical and economic water scarcity with the latter affecting more than 75% of the region (Hanjra and Qureshi, 2010). The greater proportion of agriculture (≈ 90%) is resource constrained, subsistence based and done under rain-fed conditions (van Duivenbooden et al., 2000). Under these conditions, reports of yield losses associated with water stress are common (Rockström et al., 2003). This increases the risk to food production in a region already plagued with food insecurity and a variety of socio-economic and biophysical production constraints (Ortmann and King, 2010). Increasing crop productivity with the available water is a major priority given the necessity to improve food security. There is need, therefore, to institute technologies modelled on the concept of "more crop per drop" (Tuong and Bouman, 2003) if agricultural production is to increase.

Passioura (2006) suggested that growing crops that have traits that confer plant level water management could help lessen the effects of water scarcity. The use of crop species whose genetic makeup allows for enhanced capture of available soil water for transpiration and efficiently exchange transpired water for CO_2 for sustained biomass production could improve yield production under water scarcity (Deng et al., 2006; Zegada-Lizarazu et al., 2011). For example, Kizito et al. (2007) pointed out that growing crops with deep and prolific root systems ensured extraction of water deep in the soil profile and hence minimised water lost through drainage thus increasing evapotranspiration. In addition, plants that exhibit high levels of osmotic adjustment have been shown to maintain high rates of stomatal conductance thus sustaining the exchange of transpired water and CO_2 for longer under water–limited conditions (Ahmadi Mousavi et al., 2009; Loutfy and El-Tayeb, 2012; Asina and Herralde, 2015). Therefore, it is recommended that, for water scarce agricultural systems, crops that are efficient at the capture and use of water must be used to improve productivity. Based on the above description an exemplar crop is sorghum (Allen et al., 2011; Farré and Faci, 2006; Sani et al., 2011).

Sorghum (*Sorghum bicolor* L. Moench) is the second most important cereal crop in SSA after maize and has a significant role to play in providing food security within the region (Taylor, 2003). Although praised for its ability to thrive in areas that receive as little as 300 mm annual rainfall, literature indicates that observed yields are far below potential (Aishah et al., 2011). This has mainly been attributed to water stress associated with poor agronomic and water management strategies (Rockström et al., 2010). By employing water management strategies like intercropping, rainfed production systems of sorghum can be improved (Walker and Ogindo, 2003; Ouda et al., 2007; Singh and Behari, 2012; Jun et al., 2014).

Intercropping is defined as growing two or more crops together, that is, in proximity and on the same piece of land during the same growing season (Willey, 1979). Intercropping increases spatial and temporal exploitation of water through increased root density and differences in rooting patterns of species (depth, width and length), but only if complimentary interaction between the component crops is exhibited. Under intercrop systems, there is also early attainment of full canopy cover and this reduces soil evaporation earlier in the growing season (Coll et al., 2012; Ofori et al., 2014; Walker and Ogindo, 2003). Zougmore et al. (2000) observed a 30% reduction in runoff when sorghum was intercropped with cowpea (*Vigna unguiculata* Walp). It is possible that intercropping sorghum with either cowpea or bottle gourd (*Lagenaria siceraria* (Molina) Standl.) can improve water management in rain-fed cropping systems. However, these assumptions still need to be tested rigorously to make meaningful recommendations.

Intercropping and using crops that are efficient at capturing water and exchanging it for CO_2 for biomass production can be a suitable water management strategy for resource poor farmers practicing agriculture under rainfed conditions. It was hypothesized that sorghum, cowpea, bottle gourd intercrop systems use water more efficiently and are suited to rainfed cropping systems. Therefore, the aim of the study was to evaluate growth, yield, productivity and water use as well as water use efficiency of sorghum, cowpea and bottle gourd intercrop systems under varying water regimes.

6.2 Material and Methods

6.2.1 Plant material

Three crop species, namely sorghum, cowpea and bottle gourd were used in the study. A sorghum hybrid (PAN8816) was sourced from Pannar Seeds®. PAN8816 is a medium to late maturing hybrid variety with yields ranging between 2 – 5 t ha^{-1} under optimum conditions. It is a large seeded variety with high aboveground biomass and good threshability. It is classified in the GM (good malting, no condensed tannins) category. For cowpea, brown mix variety (Capstone Seeds) was used for the study based on previous reports that suggested that it had fairly good drought tolerance (Modi and Mabhaudhi, 2013). According to Ntombela (2013), brown mix variety has a semi–erect growth habit, making it ideal for intercropping. Lastly, a bottle gourd landrace selection was collected from farmers' fields in Mereense, Richards Bay, South Africa [28°19' S; 32°06' E; 30 meters above sea level (m a.s.l.)], in 2012. Seeds were then multiplied at the University of KwaZulu–Natal, South Africa during 2012/13.

6.2.2 Experimental site

Field trials were conducted at the University of KwaZulu–Natal's Ukulinga Research Farm (29°37'S; 30°16'E; 775 m a.s.l.) over two seasons (2013/14 and 2014/15). Ukulinga Research Farm is classified as semi–arid with mean annual rainfall of 790 mm received mostly between the months of October and April. The summer months are warm to hot with an average temperature of 26.5°C. Land form at Ukulinga is colluvial fan and soils are derived from marine shales. Based on the FAO soil classification system, chromic luvisols are the dominant soils at Ukulinga and these are generally characterised as shallow brown acidic soils with low to moderate fertility. Based on profile pit description, soil texture is clay to clay–loam with an effective rooting depth of 0.6 m (Table 5. 1). Soil physical properties have been shown to affect movement and availability of soil water for plants. Based on soil texture, the soil water characteristics (bulk density (g cm^{-3}), hygroscopic water content (mm m^{-1}), permanent wilting point (mm m^{-1}), field capacity (mm m^{-1}) total available water (mm m^{-1}), saturation (mm m^{-1}) hydraulic conductivity (mm h^{-1}) were all determined using hydraulic properties calculator (http://hydrolab.arsusda.gov/soilwater/Index.htm) for each depth (Table 6.1). Results of soil chemical properties showed that the carbon (%) for the top 0.2 m layer was 2.3% while N was 0.3%. From these the initial C:N ratio was calculated as 7.67.

Table 6.1: Soil water properties at different depths for soil at the experimental site.

		BD[1]	HC[2]	PWP[3]	FC[4]	TAW[5]	SAT[6]	K_{SAT}[7]
Depth (m)	Texture	g cm^{-3}	mm m^{-1}					mm day^{-1}
0 – 0.10	Clay loam	1.29	0.34	21.04	33,54	12.50	48.66	20.90
0.10 – 0.30	Clay loam	1.47	0.69	47.61	69,94	24.63	97.89	18.18
0.30 – 0.60	Clay	1.40	2.39	79.23	110,42	34.13	149.83	13.92
Average*/Total		1.39*	3.42	147.88	213,9	71.26	296.38	17.67*

[1]Bulk density; [2]Hydroscopic moisture content; [3]Permanent wilting point; [4]Field capacity; [5]Total available water; [6]Saturation; [7]Hydraulic conductivity

6.2.3 Experimental design and layout

The experimental design was a split–plot design with sub-plots laid out in randomised complete blocks within the main plots and replicated three times. The main plot was water regime with three levels (full irrigation, deficit irrigation and rainfed). Sub–plots comprised intercrop combinations, with five intercrop combinations.

Water regimes: Full irrigation involved watering crops up to 100% of crop water requirement for the duration of the trials. For deficit irrigation, irrigation was only scheduled during periods when crop development was sensitive to water stress and thus controlling reproductive growth and development and vegetative growth with the aim of improving water use efficiency. Grain sorghum is most sensitive to water stress at initial establishment up to floral initiation and at flag leaf stage all through to yield formation (Farahani and Chaichi, 2012). Irrigation was therefore withdrawn between floral initiation and reinstated upon appearance of the flag leaf. Before planting and up to crop establishment, soil was irrigated to maintain 80% field capacity to create a conducive environment for even crop stand. During this time, a total of 123.50 and 68.00 mm was applied across all water regimes for 2013/14 and 2014/15 growing season. Therefore, rainfed treatments were established with irrigation to allow for maximum plant stand. Following that, no supplementary irrigation was applied. Irrigation scheduling was based on daily crop water requirement calculated from the product of sorghum crop factors (K_c) as published in FAO No. 56

(Allen et al., 1998) and Priestley-Taylor (PT) reference evapotranspiration (ET_o) values obtained from an automatic weather station (AWS) located 1 km away from the experimental field. The K_c values for grain sorghum were K_c initial = 0.30 (33 days), K_c mid = 1.10 (64 days), and K_c end = 0.55 (44 days). The durations in brackets indicate the corresponding periods in days for which the crop factors were applied.

Crop water requirement (ET_c) was determined as described by (Allen et al., 1998):

$$ET_c = ET_o * K_c \qquad \text{Equation 6.1}$$

where: ET_c = crop water requirement in mm,

ET_o = reference evapotranspiration in mm, and

K_c = crop factor.

In the event of rainfall, irrigation scheduling was adjusted accordingly using crop water requirement for that developmental stage and rainfall information.

Intercrop: The component crops were sorghum, cowpea and bottle gourd. The intercropping treatments were: sorghum (sole), cowpea (sole), bottle gourd (sole), sorghum + cowpea (intercrop) and sorghum + bottle gourd (intercrop). According to Chaves et al. (2013), grain cereals remain important fore-drivers of food security in Africa's research agenda; for this reason, the intercropping system was designed as an additive intercrop. Briefly, additive intercropping is when a component crop is added into another (main component crop) such that the additional crop increases final plant population relative to the main crop. Sorghum was considered as the main crop and was sown at 100% of its recommended plant population in pure and intercrop stands. Cowpea and bottle gourd were then "added" to the sorghum by planting additional rows between rows of sorghum.

Individual plot sizes for each treatment measured an area of 24.75 m^2. All rows were 5.5 m long and inter-row spacing for sorghum (sole and intercrop treatment) and sole cowpea and sole bottle gourd was 0.75 m. For the intercrop treatments, rows for intercrops were made in the middle (0.375 m) of sorghum rows. Under semi-arid conditions, du Plessis (2008) recommended a plant population of 26 666 plants ha^{-1} for sorghum. This ensures low competition for resources such as solar radiation, water and nutrients. To attain this population, an in-row spacing of 0.50 m was used for sorghum. A similar plant population was also used for sole cowpea; however, under intercropping the in-row spacing was increased to 1 m. For sole and intercropped bottle gourd, the in-row spacing was 1.86 and 2.75 m, respectively.

6.2.4 Data collection

Climate data*:* Daily weather data were obtained from an automatic weather station (AWS) located less than 1 km from the experimental field and within Ukulinga Research Farm. The AWS is part of the Agricultural Research Council – Institute for Soil, Climate and Water (ARC–ISCW) network of automatic weather stations. Daily weather parameters that were considered included maximum (T_{max}) and minimum (T_{min}) air temperature (°C), solar radiation (Rad, MJ m^{-2}), rainfall (mm) and PT- ET_o (mm).

Plant growth and development: Data collection included emergence measured up to crop establishment (90% emergence) in sorghum as the main crop of interest. Thereafter, measurements of plant height (PH), leaf number (LN), leaf area index (LAI), stomatal conductance (g_s), chlorophyll content index (CCI), relative water content (RWC) and biomass accumulation were collected on a weekly basis for all component crops. Stomatal conductance was measured using a steady state leaf porometer (Model SC–1, Model SC-1, Decagon Devices, USA) on the abaxial surface of the top most fully expanded leaf. Due to unavailability of equipment in the first season, second season results of stomatal conductance were only presented. Chlorophyll content index was measured with a SPAD502-*Plus* chlorophyll meter (Konica Minolta, USA) on the adaxial surface of the top most fully expanded leaf.

Relative water content was determined weekly from flowering up to the end of grain filling using the method outlined by Muchow and Carberry (1990). One leaf was sampled from each component crop $plot^{-1}$. Immediately after excising the leaf blade, leaves were wrapped in aluminium foil, placed in a plastic zip–lock bag and kept in a cool place for two hours. Thereafter, three disks measuring 0.5 cm each were cut out and immediately weighed to determine fresh mass (FM). To obtain turgid mass (TM), leaf disks were placed in petri dishes containing 25 mℓ of distilled water and left to imbibe for 16 hours at room temperature before being weighed. Following this, leaf disks were than dried at 80°C for 72 hours to obtain dry mass (DM). Relative water content was then calculated as:

$$RWC\% = \frac{FM - DM}{TM - DM} X\ 100\% \qquad \text{Equation 6.2}$$

where: RWC = relative water content (%),

FM = fresh mass (g),

DM = the dry mass (g), and

TM = the turgid mass (g).

Leaf area index, which is the one–sided green leaf area per unit ground surface area occupied by the plant, was also determined from measurements of leaf area. Leaf area index was determined as follows:

$$LAI = \frac{LA}{A} \ (m^2 m^{-2})$$ Equation 6.3

where: LAI = leaf area index (m^2 m^{-2}),

LA = leaf area (m^2), and

A = the land area (m^2) occupied by the plant.

Sorghum crop development was monitored based on phenological stages described by Rao et al. (2007). Observed phenological stages were end of juvenile stage, floral initiation, flag leaf appearance, flowering, start and end of grain filling as well as times to physiological and harvest maturity. A phenological stage was deemed to have occurred when it was observed in at least 50% of experimental plants. Observations of crop phenology were recorded in calendar days and later converted to thermal time using method 2 as described by (McMaster and Wilhelm, 1997):

$$\boldsymbol{GDD = \left[\frac{T_{max}+T_{min}}{2}\right] - T_{base}}$$ Equation 6.4

where: GDD = growing degree days (°Cd),

T_{max} and T_{min} = maximum and minimum temperatures, respectively, and

T_{base} = base temperature. If $T_{max} < T_{base}$ then $T_{max} = T_{base}$ and if $T_{min} < T_{base}$ then $T_{min} = T_{base}$, T_{base} = 8°C

Productivity of cropping systems*:* Productivity of the intercrop systems was evaluated using Land Equivalent Ratio (LER) as described by Willey (1979):

$$LER = L_a + L_b = \frac{Y_a}{S_a} + \frac{Y_b}{S_b}$$ Equation 6.5

where: LER = land equivalent ration,

L_a and L_b = LERs of component crop a (sorghum), and b (cowpea or bottle gourd), respectively, and

Y_a and Y_b represent intercrop yield component crop a (sorghum), and b (cowpea or bottle gourd), respectively, while S_a and S_b are their respective sole.

Yield determination*:* Harvesting of each component crop across the different treatments was done at harvest maturity. Since cowpea variety brown mix is a semi–determinant crop, sequential harvesting of pods began when there was first sign of pod drying. However, during the 2014/15 season, pods where repeatedly eaten by monkeys, therefore, results do not show pod and grain yield. During 2013/14, sorghum was harvested at harvest maturity, however similar to cowpea, repeated monkey and bird attacks during 2014/15 resulted in harvesting it at soft dough stage. At harvest for sorghum, above ground plant matter of six representative plants of sorghum were taken for determination of yield parameters (harvest index) and yield. Similarly, cowpea was also harvested for determination of yield parameters (harvest index) and overall yield. Panicles and pods were separated from the whole plant and dried in a glasshouse until seeds shuttered from panicle and pods. Thereafter grain was shelled and, mass and grain moisture were determined. At harvest maturity of bottle gourd, fruits were separated from mother plant. Similarly, harvesting of bottle gourd was early due to monkey attacks. Fruits and mother plant were also placed in a glasshouse for drying and they were cracked open to hasten drying process of fruits. Fruits were weighed every second day and when there was no loss in mass at two consecutive weightings, fruits were considered dry and final biomass mass was determined. Thereafter harvest index (HI) was determined as:

$$HI = \frac{Yg}{B} \qquad \text{Equation 6.6}$$

where: HI = harvest index (%),

Y_g = economic yield based on grain yield (kg), and

B = aboveground biomass (kg).

Harvest index of each cropping system across the water regimes was estimated as the average of the sum of each component HI.

Water use: Water use (ET) for each treatment was calculated as the residual of a soil water balance:

$$ET = P + I - D - R - \Delta SWC \quad \text{Equation 6.7}$$

where: ET = evapotranspiration (mm),

P = precipitation/rainfall (mm),

I = irrigation (mm),

D = drainage (mm),

R = runoff (mm), and

ΔSWC = changes in soil water content (mm).

Runoff (R) was assumed to be zero since it was negligible in the plots as they had a slope of less than 5%. Drainage was also considered negligible since the observed impeding layer at 0.6 m restricted downward movement of water beyond the root zone.

Changes in soil water content (SWC) were measured using a PR2/6 profile probe connected to an HH2 handheld moisture meter (Delta–T, UK). The soil profile at Ukulinga is shallow with an effective rooting depth of 0.60 m (Table 6.1). The PR2/6 profile probe has sensors positioned at 0.10, 0.20, 0.30, 0.40, 0.60 and 1.00 m along the probe. Sensors used in the analysis of SWC where the first five (0.10 – 0.60). Due to small variations occurring at depths of 0.20 and 0.30 m, and 0.40 and 0.60 m, respectively, results for SWC were only presented for depths of 0.10, 0.30 and 0.60 m. Weekly rainfall (R) was obtained from data obtained from the AWS. Irrigation was applied using sprinklers and after each irrigation event, amount of water added (I) was determined from rain gauges randomly placed across the experimental plots. It should be noted that, during 2013/14 around the time of grain filling, a water pipe, which directly supplies irrigation water from the local municipality to the farm, burst such that there was no water for irrigation until harvest of experiment.

To determine whether intercropping resulted in changes in water use, the following equations suggested by Morris and Garrity (1993) were used:

$$\Delta WU\ (\%) = \left[\left(\frac{WU_{ic}}{P_a WU_{sa} + P_b WU_{sb}}\right) - 1\right] * 100\% \quad \text{Equation 6.8}$$

where: WU_{ic}, WU_{sa} and WU_{sb} = the water use in intercropping, sole cropping species A and sole cropping species B, respectively, and Pa and Pb are the proportions of species A and B in the intercrop, given by Pa = Da/(Da + Db) with Da and Db being the density in intercropping relative to sole cropping of species A and B, respectively.

Water use efficiency: Water use efficiency was only calculated for the sole treatments since it was not possible to separate water use for each component crop in the intercrop systems. Water use efficiency of sole cropping system was therefore calculated as follows:

$$WUE_{Y/B} = \frac{Y/B}{WU}(kg\ mm^{-1}\ ha^{-1}) \quad \text{Equation 6.9}$$

where: WUE = water use efficiency (kg mm^{-1} ha^{-1}),

Y = the economic yield (kg ha^{-1}),

B = final biomass (kg $ha^{-1)}$ and

ET = the water use (mm).

To determine whether intercropping resulted in changes in water use efficiency the following equation suggested by Morris and Garrity (1993) was used:

$$\Delta WUE\ (\%) = \left(\frac{\frac{Y_{ic}}{WU_{ic}}}{\left(\frac{P_a Y_{sa}}{WU_{sa}}\right) + \left(\frac{P_b Y_{sb}}{WU_{sb}}\right)} - 1 \right) * 100\% \quad \text{Equation 6.10}$$

where: Y_{ic}, Y_{sa} and Y_{sb} = the yields in intercropping and sole cropping of species A and B, respectively.

For interpretation, when ΔWU and ΔWUE are greater than zero, WU and WUE are assumed higher in the intercrop system relative to the sole crop.

6.2.5 Agronomic practices

Prior to planting, soil samples were obtained from the field trial site and analysed for soil fertility and textural analyses. Based on results of soil fertility analyses, an organic fertiliser, Gromor Accelerator® (30 g N kg^{-1}, 15 g P kg^{-1} and 15 g K kg^{-1}) was applied to supply 52 kg N ha^{-1}. Fertiliser application was designed to meet the nutritional requirements for sorghum, the main crop, and applied six weeks after emergence.

Land preparation involved ploughing, disking and rotovating to achieve fine tilth. Planting was done by hand; planting depth for all crops ranged from 2–3 cm. For sorghum, rows were opened and seed sown within the rows. Upon full establishment (90% emergence), sorghum was thinned to the required spacing; excess seedlings were used for gap filling. Routine weeding was done using hand hoes. Insect pests and animal attacks were scouted for at each visit to the field. An electric fence was erected to protect the trials from animal attacks.

6.2.6 Statistical analyses

Bartlett's test was done to determine homogeneity of variances for all measured variables before combining data across the seasons. The test did not show homogeneity of variances for crop growth and physiology across the seasons, thus combined analysis was not done. Combined analysis was done for yield and yield components as they showed homogeneity. Data collected was subjected to analysis of variance (ANOVA) using GenStat® (Version 16, VSN International, UK) and means of significantly different variables separated using Duncan's test in GenStat® at the 5% level of significance.

6.3 Results

6.3.1 Weather data

Weather data for the two growing periods was consistent with long-term weather data for Ukulinga (Section 6.2). Comparing the two growing periods (2013/14 and 2014/15), weather conditions were different by virtue of crop establishment occurring at different times within the growing season (Fig 6.1). Although maximum temperatures were similar (25.43 and 25.98°C for 2013/14 and 2014/15, respectively), minimum temperature in 2014/15 (16.61°C) was 2.35°C higher than the observed temperature during 2013/14 (18.96°C). Maximum and minimum temperatures were consistent with long-term temperature averages of 25.63 and 16.89°C. This resulted in a high rate of GDD (°Cd) (1965.09 in 2013/14 and 2412.03 in 2014/15). High accumulation rate of GDD would insinuate hastened crop development. Solar radiation received in 2014/15 (2543.46 MJ m^{-2}) was slightly higher than 2013/14 (2433.42 MJ m^{-2}) (data not shown).

Rainfall in 2014/15 was 26.31% higher than in 2013/14 and based on skewness it was more normally distributed (4.33) than rainfall received during 2013/14 season (7.00). There were more incidences of days when no rain was recorded in 2013/14 (105 days) than 2014/15 (49 days) (Fig 6.1). The observed results suggest that the possibility of intermittent water stress was higher in 2013/14 than 2014/15. Cumulative reference evapotranspiration was 502.61 and 493.75 mm during 2013/14 and 2014/15, respectively. This resulted in a deficit of 184.14 and 91.49 mm during 2013/14 and 2014/15, respectively (Fig 6.1). Observed results are consistent with long-term water deficits (135.26 mm, standard deviation = 65.56 mm) experienced at Ukulinga. During 2013/14, irrigation applied in the FI treatment was 286.50 mm giving an excess of 102.36 mm. Under deficit irrigation, water applied was 208.05. During 2014/15, irrigation applied in the FI treatment was 208.05 mm giving an excess of 44.51 mm. Under deficit irrigation, 136.00 mm of water was applied giving an excess of 23.86 mm. Based on observed weather, the 2014/15 was more conducive for plant growth. Incidences of hailstorms were more frequent during 2014/15 (6th and 13th February 2015) season than during 2013/14 (21st February 2014) (Fig 6.1). During 2014/15, hail storms coincided with the late vegetative stage hence making plants more susceptible to defoliation compared to 2013/14 when plants were at the early vegetative stage and suffered relatively less defoliation. With each event, there was substantial loss in plant canopy size.

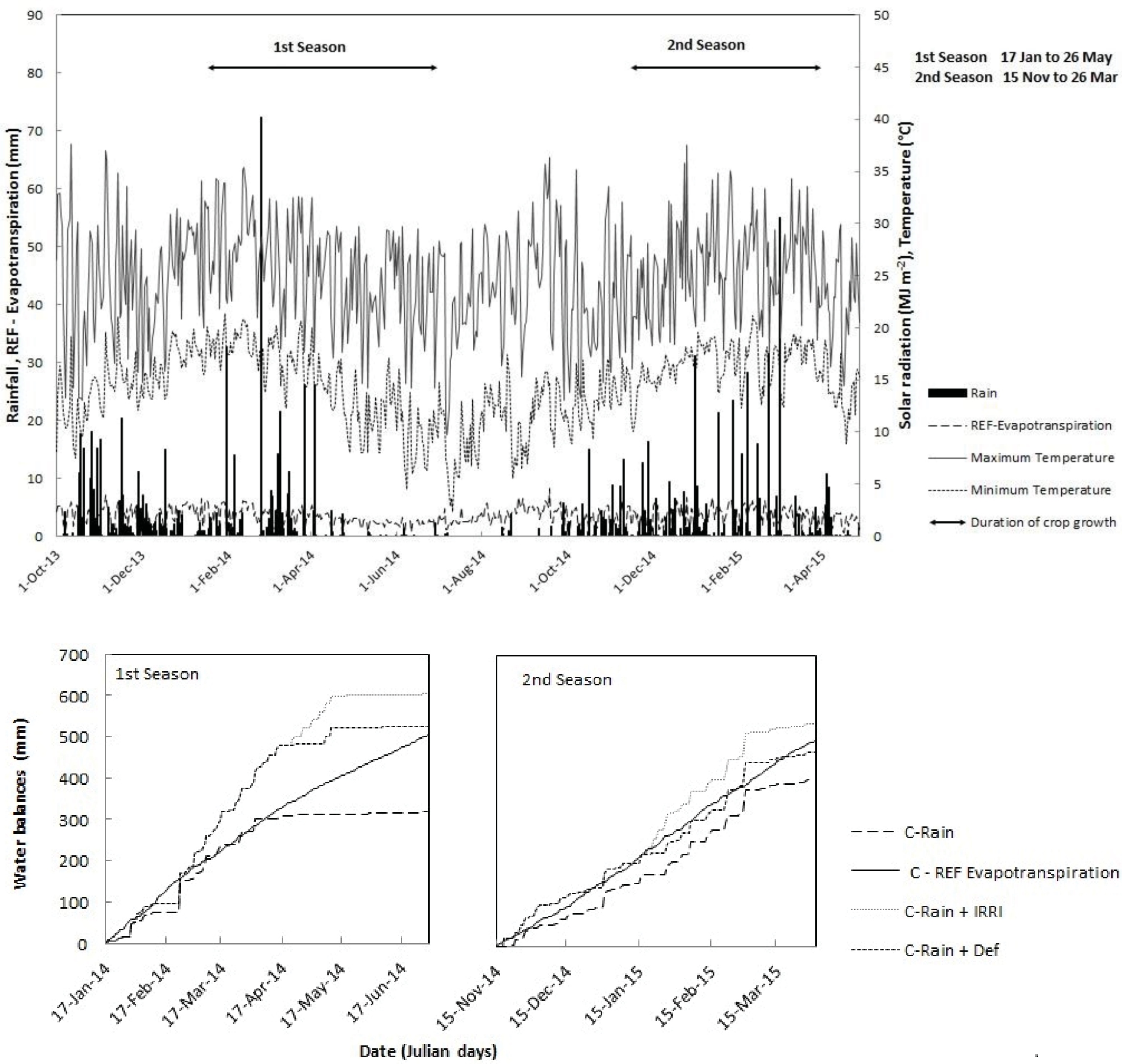

Figure 6.1: Daily temperature (maximum and minimum) and reference evapotranspiration (REF –Evaporation) observed at Ukulinga, KwaZulu–Natal South Africa, and a comparison of cumulative rainfall and cumulative REF –evapotranspiration at the site.

6.3.2 Soil water content

Soil water content was different across seasons, soil layers, water regimes and intercropping treatments (Fig 6.2). Based on mean values, during 2013/14 SWC was more evenly distributed (standard deviation = 8.34 mm) across soil layers, water regimes and intercropping treatments when compared with 2014/15 (standard deviation = 10.57 mm) and this was attributed to less rain and irrigation events (Fig 6.2). It was observed that SWC during 2013/14 started off high and gradually decreased after boot stage. This coincided with the time when there was no supply of water to the experiment and an increase in the demand of water by crops. Conversely, the reverse was observed in 2014/15, and this was attributed to increased frequency of rainfall and irrigation. Overall, average SWC during 2014/15 was higher (195.27 mm) than during 2013/14 (181.59 mm). The observed differences were associated with variation in amounts in total rainfall and irrigation received during the two growing seasons.

During the 2013/14 and 2014/15 growing seasons, the trend for SWC across the water regimes was such that DI (213.00 and 204.69 mm) > RF (170.97 and 203.80 mm) > FI (160.81 and 177.81 mm, respectively). It was interesting to note that under DI SWC was high while the least SWC was observed under FI. Intercropped plots had marginal differences in average SWC relative to sole sorghum plots (SS) during 2013/14 and 2014/15 (SB – 0.05 and 2.05%, SC – 0.04 and 8.71%, respectively). Soil water content of SB was consistently stable as highlighted by the low standard deviation (20.96) across water regimes and growing seasons.

During both growing seasons, SWC in the first layer (0.00 – 0.10 m) was consistently below PWP and there were no variations across the treatments. In the second layer, variations were observed across growing seasons and water regime and cropping system. During 2013/14, SWC ranged between 19.10 - 77.55 mm with a mean value of 36.15 mm. Within the same growing season, plots grown under DI had highest average SWC of 54.78 mm within this depth while low SWC was observed under FI (28.65 mm) at the same depth. In the second layer, intercropping resulted in a reduction in SWC [SB (-99.43%) and SC (-26.42%)] relative to SS. During 2014/15 growing season, range for SWC within the 0.1 – 0.3 m was between 26.84 – 87.75 mm. The mean value was 21.87% higher than what was observed in 2013/14. Within the same year, DI plots had an average SWC of 54.93 mm within in the second layer while low SWC was observed under FI (36.06 mm) at similar depth. Intercropping resulted in an increase in SWC (SB – 14.57% and SC – 26.67%) in the second layer relative to SS. Observed results would suggest water extraction by intercrop plots in the second layer was more predominant in the drier year. It was interesting to note that SWC at depths of 0.30 to 0.60 m was consistently around FC (110.42 mm) for 2013/14 (129.17±18.89) and around saturation (149.83 mm) for 2014/15 (147.83±15.56) (Fig 6.2).

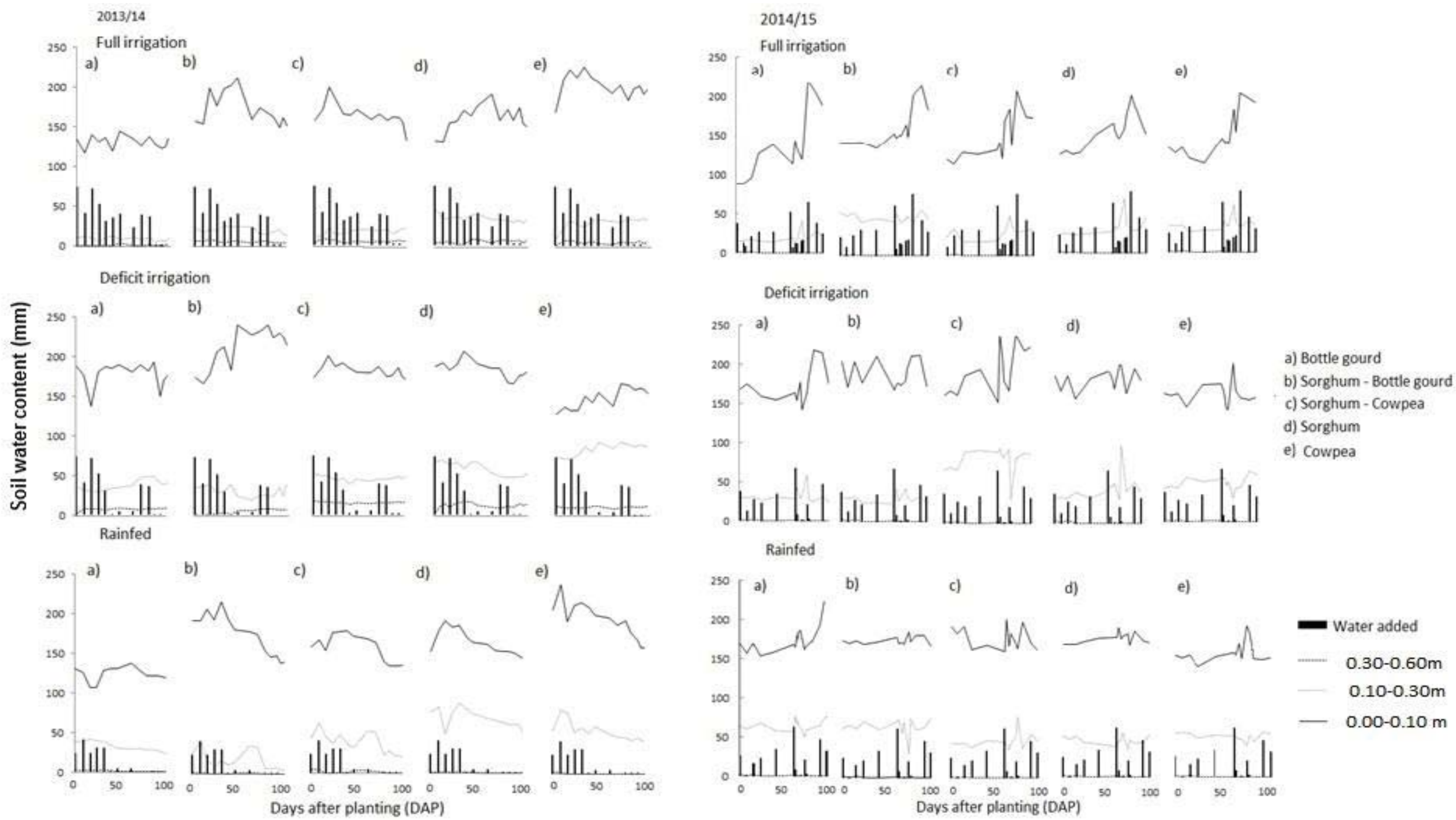

Figure 6.2: Soil water content (mm) at depths 0 – 0.10 m, 0.10 – 0.30 m and 0.30 – 0.60 m for the different cropping systems [sole sorghum (SS), sole cowpea (C), sole bottle gourd (B), sorghum – cowpea (SC) and sorghum - bottle gourd (SB)] grown under different water management regimes [full irrigation (FI) deficit irrigation (DI) rainfed conditions (RF)] for 2013/14 and 2014/15 planting season.

6.3.3 Crop physiology

Interaction of water regime and cropping system significantly ($P<0.05$) influenced sorghum CCI in each growing season (Fig 6.3). During 2013/14, CCI was significantly ($P < 0.05$) higher under FI (43.80) relative to DI (41.01) and RF (40.18). Observed results are in line with improvements in water availability (FI > DI> RF) (Section 3.1). Under FI and RF conditions, intercropping had no significant effect on sorghum CCI. Under DI, intercropping sorghum with cowpea (SC) showed higher (6.56%) CCI while intercropping it with bottle gourd (SB) resulted in low (-6.34%) CCI, relative to sorghum under SS (Fig 6.3). During 2014/15, CCI was significantly ($P < 0.05$) higher under RF (47.42) relative to DI (45.32) and FI (45.23) conditions. Under DI and RF conditions, CCI was significantly ($P <0.05$) lower for SC (-6.78%) and SB (-3.24%), relative to SS (Fig 6.3). Under FI, intercropping sorghum with cowpea improved CCI of sorghum by 3.31% relative to SS.

The interaction of water regime and cropping system significantly ($P < 0.05$) influenced RWC during both growing seasons (Fig 6.3). During 2013/14 growing season, results showed that the trend for sorghum RWC across water regime was FI (83.33%) > DI (81.75%) > RF (78.13%). Sorghum intercropped with cowpea had low RWC (-2.78%) under FI and RF conditions relative to SS. Under FI, intercropping sorghum with bottle gourd improved (+2.11%) RWC for sorghum, relative to SS (Fig 6.3). During 2014/15, the trend of sorghum RWC was FI (82.23%) for significantly lower than DI (85.23%) and RF (86.27%). Regardless of water regime sorghum grown in SC had the least RWC (-3.51%) relative to that of SS (Fig 6.5). Under FI and RF, leaf RWC of sorghum grown in SB was not significantly different to sorghum grown in SS.

Significant variations ($P < 0.05$) were observed for g_s of sorghum in response to the interaction of water regime and cropping system (Fig 6.3). Increasing levels of SWC resulted in an overall increase in g_s [FI (359.85 mmol m^{-2} s^{-1}) < DI (375.85 mmol m^{-2} s^{-1}) < RF (460.85 mmol m m^{-2} s^{-1})]. Stomatal conductance of sorghum in SC was significantly higher (15.94%) while SB was lower (-2.20%) in comparison to that which was grown as SS (381.39 mmol m^{-2} s^{-1}) (Fig 6.3). Under RF, g_s of sorghum intercropped with cowpea was statistically similar to that of SS. However, under DI and FI intercropping sorghum with cowpea improved (23.9%) g_s of sorghum relative to SS. The observed fluctuations of g_s over time across water regimes were in response to weather (relative humidity and air temperature) and SWC variability.

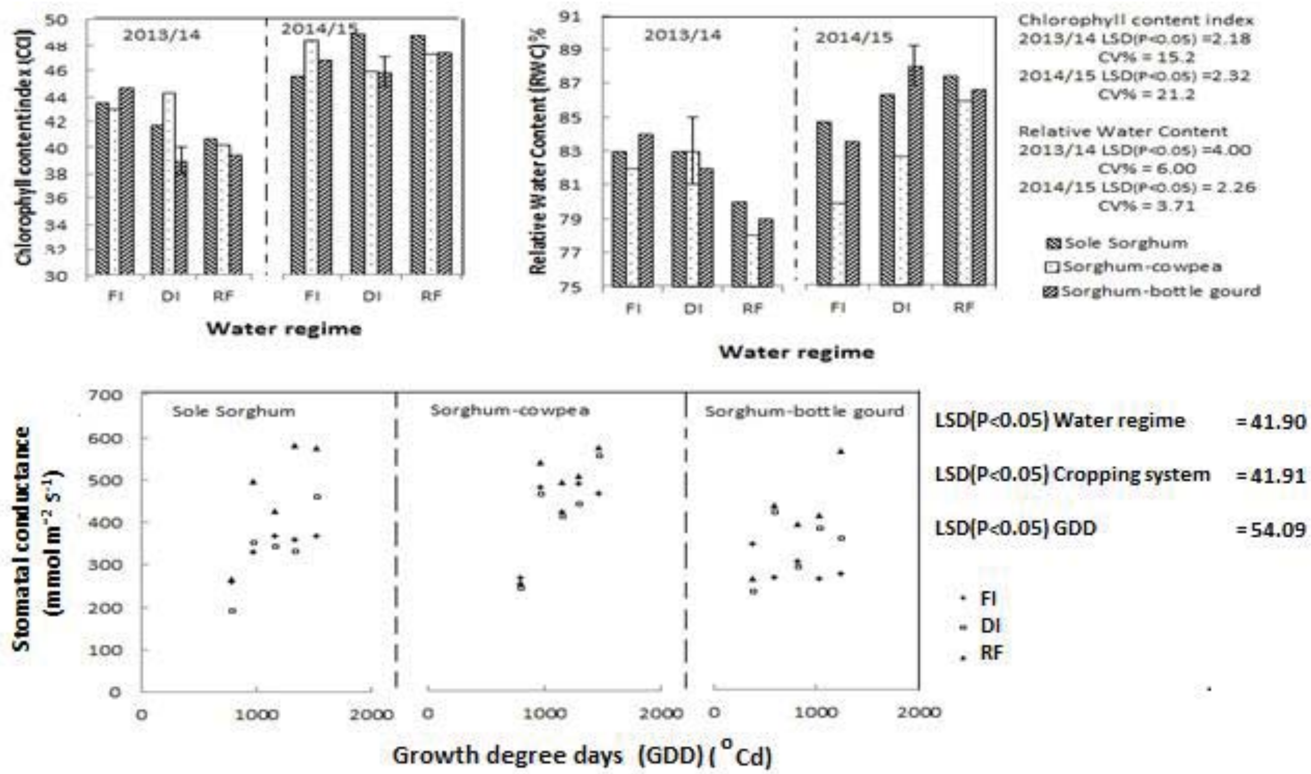

Figure 6.3: Comparison of sorghum chlorophyll content index (CCI), relative leaf water content (RWC) and stomatal conductance in response to season (2013/14 and 2014/15), cropping system [sole sorghum (SS), sorghum – cowpea (SC) and sorghum - bottle gourd (SB)] and water regime [full irrigation (FI) deficit irrigation (DI) rainfed conditions (RF)] over time [calculated as sorghum growth degree days (GDD)].

The trend of results for the 2014/15 growing season was inconsistent with observations of the 2013/14 season. During 2014/15 growing season, water regime had a significant ($P < 0.05$) effect on sorghum plant height ($P < 0.05$) and leaf number ($P < 0.05$) while cropping system was only observed to significantly influence ($P < 0.05$) leaf number (Fig 6.4). The trend for sorghum plant height was RF > DI > FI (69.33, 67.34 and 66.34 cm, respectively) (Fig 6.4) while for leaf number it was RF > FI > DI (7.75, 7.37 and 6.67). Overall, intercropping sorghum with cowpea resulted in fewer leaves (10 %) when compared with SS while SB improved sorghum leaf number by 5%.

Tillering in sorghum was less pronounced during 2013/14 than 2014/15. This was associated with improved water availability during 2014/15 relative to 2013/14 (Fig 6.4). Significant differences ($P < 0.05$) were observed for tillering in response to water regime during 2013/14. Although low, tillering was higher under FI (0.2 tillers) followed by DI (0.1 tillers) while no tillers were observed under RF conditions (Fig 6. 4). During 2014/15, the interaction of water regime and cropping system had a significant effect ($P < 0.05$) on tillering. Overall, the trend for tillering across water regimes of sorghum grown under RF conditions was significantly higher (1.17) than under DI (1.02) and FI (1.06). Sorghum grown in SB had 24% and 7% more tillers relative to SS when grown under DI and RF, respectively. Sorghum grown in SC had 12% and 5% less tillers relative to SS when grown under DI and RF, respectively.

Although the seasonal effect of sorghum LAI was not statistically analysed, it was observed that it was 56.23% higher in 2014/15 than 2013/14. The higher LAI observed could be attributed to time of planting and improved water availability. In the second season, the trial was established earlier and this must have coincided with optimum climatic conditions for vegetative growth. In addition, there was improved water availability due to high and more frequent rainfall. Leaf area index for sorghum was significantly ($P < 0.05$) affected by water regime (Fig 6.4). This was more evident during 2014/15 compared with 2013/14 season. During 2013/14 growing season, although differences were small but statistically significant, the trend for average LAI was FI (0.43) > DI (0.40) > RF (0.39). During 2014/15 season, the trend for LAI was RF (1.43) > DI (0.90) > FI (0.89). Within 2013/14, growing sorghum with either cowpea or bottle gourd significantly ($P < 0.05$) improved (35.87 and 23.78%, respectively) overall system LAI relative to SS (data not shown).

Results of LAI during the two growing seasons were consistent with observations of plant physiology and PH, LN and tillers/plant. The observed fluctuations in LAI during 2014/15 corresponded with vegetative loss due to hail damage (Fig 6.4). Conversely, in 2014/15, overall

LAI for sorghum was substantially ($P < 0.05$) improved (86.96% and 115.13%) when intercropped with cowpea (SC) and bottle gourd (SB), respectively (results not shown). Based on slope value of regressed LAI and GDD, rate of increase of LAI under intercropping was higher when sorghum was intercropped with either cowpea (slope = 0.007 and $r^2 = 0.84$) or bottle gourd (slope = 0.006 and $r^2 = 0.72$) relative to sole sorghum (slope = 0.002 and $r^2 = 0.74$).

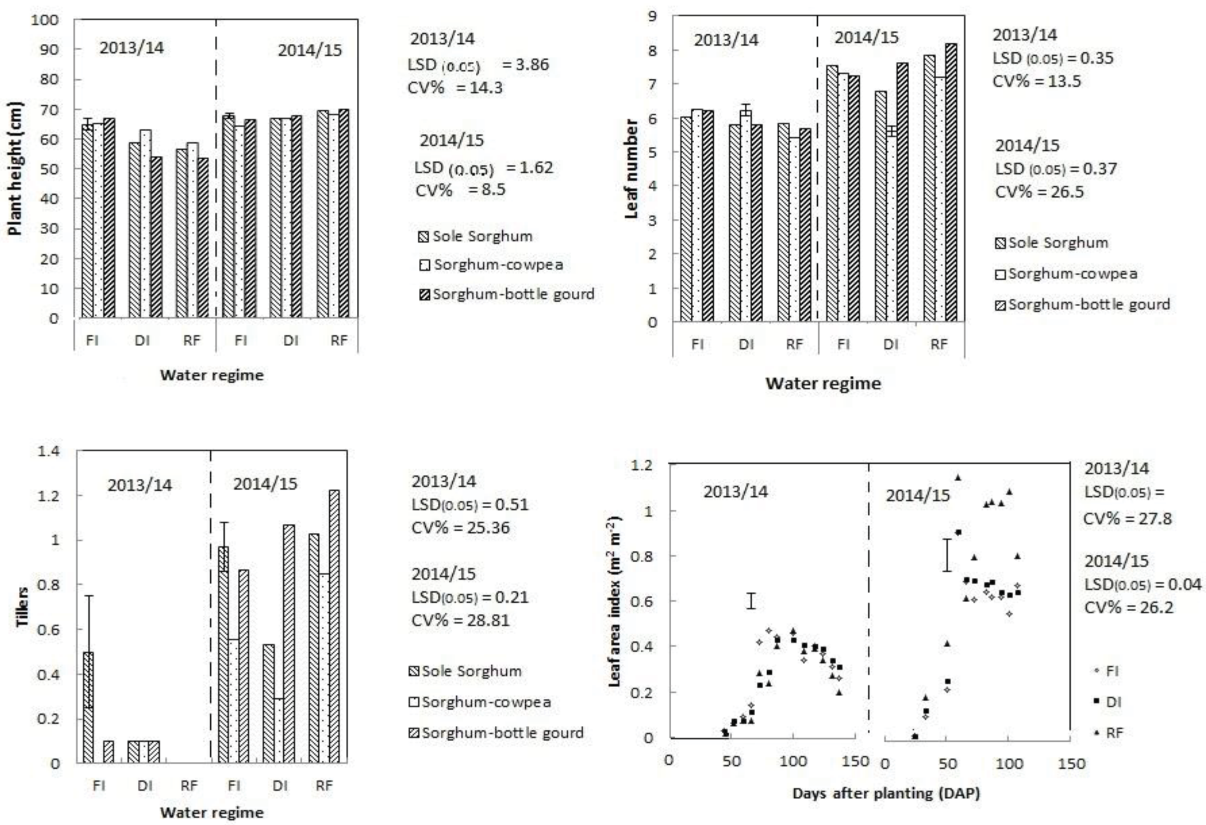

Figure 6.4: Comparison of sorghum growth parameters (plant height, tiller number, leaf number and leaf area index) in response to cropping system [sole sorghum (SS), sorghum – cowpea (SC) and sorghum - bottle gourd (SB)] and different water regimes [full irrigation (FI) deficit irrigation (DI) rainfed conditions (RF)].

6.3.5 Crop phenology

During 2013/14 growing season, emergence, end of juvenile stage and floral initiation of sorghum occurred at 266.31, 514.04 and 983.78 °Cd, respectively. Time from floral initiation to flag leaf appearance was 205.89 °Cd and from flag leaf appearance to boot stage was 165.37 °Cd. Time between boot stage and 50% flowering was 131.45 °Cd while time between 50% flowering and soft dough stage was 98.45 °Cd. Harvesting occurred at 1889.02 °Cd.

During 2014/15 growing season, emergence, end of juvenile stage and floral initiation of sorghum occurred at 75.86, 280, 69 and 666.79 °Cd, respectively. Time from floral initiation to flag leaf appearance was 207.22 °Cd and from flag leaf appearance to boot stage it was 162.72 °Cd. Time between boot stage and 50% flowering was197.78 °Cd while time between 50% flowering and soft dough stage was 137.78 °Cd. Harvesting occurred at 1599.16 °Cd.

The delay in emergence, end of juvenile stage and floral initiation during 2013/14 relative to 2014/15 was associated with low soil water availability in the 0 – 0.10 m layer at planting and subsequent seed establishment. The hastened development observed during 2013/14 relative to 2014/15 could be associated with observed reduction in SWC towards the end of the growing season. Early harvesting for 2014/15 was due to persistent animal attack.

6.3.6 Yield and yield components

Final biomass yield for sorghum was significantly ($P < 0.05$) influenced by the interaction of season and water regime (Table 6.2). Sorghum biomass was significantly ($P < 0.05$) higher (10.21%) during 2013/14 in comparison to 2014/15. For the 2013/14 growing season, observed trend was FI (3.09 t ha^{-1}) > DI (2.92 t ha^{-1}) > RF (2.36 t ha^{-1}) (Table 6.2). On the other hand, the trend for biomass during 2014/15 was RF (2.66 t ha^{-1}) > DI (2.48 t ha^{-1}) > FI (2.31 t ha^{-1}). Observed final biomass for both seasons was consistent with observed growth patterns within each growing period (Table 6.2). Final biomass for sorghum grown under DI did not vary significantly across the two growing seasons suggesting stability. However, yield was about 16% higher ($P < 0.05$) in 2013/14 relative to 2014/15 and this could be attributed to high final biomass attained (Table 6.2).

Final biomass of cowpea was significantly ($P < 0.05$) affected by the interaction of season and cropping system (Table 6.2). Final biomass was 500% higher during 2014/15 in contrast to 2013/14. This was attributed to improved growth, and increased canopy size experienced during 2014/15 (Section 6.3.1). Cowpea yield was 50% lower ($P < 0.05$) when intercropped relative to the sole crop. Low yields were associated with lower growth and suppressed physiology in the intercrop relative to the sole crop (Table 6.3).

Final biomass for bottle gourd was significantly ($P < 0.05$) affected by season and cropping system interaction. It was also significantly ($P < 0.05$) affected by water regime. Bottle gourd biomass was 9.16% higher during 2014/15 relative to 2013/14 (Table 6.3). Intercropping bottle gourd resulted in 55.83% and 45.63% less biomass during 2013/14 and 2014/15, respectively, relative to its sole crop (Table 6.3). Mean values of final biomass for water regimes showed that final biomass under DI (4.00 t ha^{-1}) was significantly higher than under FI (2.67 t ha^{-1}); final biomass under RF conditions (2.28 t ha^{-1}) was statistically similar to FI. Fruit yield for bottle gourd was significantly ($P < 0.05$) higher (73.89%) during 2013/14 in comparison to 2014/15. This subsequently resulted in significant ($P < 0.05$) differences in HI across the seasons where it was higher (72.45%) during 2013/14 relative to 2014/15 (Table 6.3).

Table 6.2: Crop growth response for cowpea and bottle gourd in response to season (2013/14 and 2014/15), cropping system (SC – sorghum cowpea, SB – sorghum bottle gourd) and water regime (FI – full irrigation, DI – deficit irrigation and RF – rainfed).

Cropping system	Water regime	2013/14 Vine length (cm)	Leaf number	Branches	LAI[5] ($m^2 m^{-2}$)	SLA[6] ($g m^{-2}$)	2014/15 Vine length (cm)	Leaf number	Branches	LAI ($m^2 m^{-2}$)	SLA ($g m^{-2}$)
Sole Cowpea	FI[1]	35.44b3	25.17c	2.70a	0.31d	103.30	83.67bc	57.12b	5.63b	1.12c	235.12
	DF	27.21a	21.55b	2.60a	0.17b	95.90	93.33c	61.23b	5.33b	1.00c	245.18
	RF	25.42a	15.00a	2.33a	0.14b	129.40	81.00b	56.20b	5.33b	1.13c	268.37
MEAN		29.36	20.57	2.54	0.21	109.53	86.00	58.18	5.43	1.08	249.56
Sorghum - Cowpea	FI	38.25b	25.29c	3.70b	0.14b	115.30	63.36a	39.20a	4.33a	0.36a	251.10
	DF	28.76a	22.08b	3.24b	0.19b	119.30	69.51a	41.12a	6.66c	0.53b	267.20
	RF	29.20a	14.80a	3.46b	0.06a	127.50	85.67b	41.63a	5.33b	0.61b	294.35
MEAN		32.07	20.72	3.47	0.13	120.70	72.85	40.65	5.44	0.50	270.88
$LSD_{(P<0.05)}$ WR[2]		3.71**	0.91**	0.29	0.03	30.68	7.78	5.61	0.50	0.11	67.70
$LSD_{(P<0.05)}$ INT		3.03	0.74	0.24*	0.03	25.05	6.30	4.62*	0.40	0.09	55.31
$LSD_{(P<0.05)}$ WR * INT		5.25	1.28	0.41	0.05*	43.39	10.91**	7.92	0.62**	0.16*	95.80
Sole Bottle gourd	FI	85.50d	14.33	*	0.14	425.00b	124.60ab	11.73a	1.89ab	0.15ab	178.00a
	DF	69.80c	14.41	*	0.13	150.00a	184.80cd	18.12c	2.80cd	0.27c	243.00abc
	RF	69.90c	13.84	*	0.14	194.00a	212.50d	18.24c	2.83cd	0.34d	335.00c
MEAN		75.07b	14.19b	*	0.14b	256.33	173.97b	16.03	2.51	0.25b	252.01
Sorghum - Bottle gourd	FI	54.40b	10.75	*	0.08	230.00a	111.00a	13.08a	1.50a	0.10a	174.00a
	DF	36.90a	8.87	*	0.08	270.00a	154.30bc	15.65b	2.50bc	0.18b	328.00bc
	RF	37.10a	8.43	*	0.05	194.00a	170.80c	17.00bc	3.44d	0.20b	231.00ab
MEAN		42.80a	9.35a	*	0.07a	231.33	145.37a	15.24	2.48	0.16a	244.33
$LSD_{(P<0.05)}$ WR		11.96**[4]	2.46	*	0.03	108.1*	31.10**	3.91**	0.75**	0.06*	98.40*
$LSD_{(P<0.05)}$ INT		9.70**	2.01**	*	0.03**	88.30	25.39*	3.19	0.61	0.05*	80.41
$LSD_{(P<0.05)}$ WR * INT		16.91	3.48	*	0.04	152.9	43.98	5.53	1.06	0.09	139.2

[1]Full irrigation - FI, Deficit irrigation - DI, Rainfed – RF; [2]WR – Water regime, INT – cropping system; [3]Means followed by the same letter indicate that they were not significantly different ($p < 0.05$) from each other; [4]*, ** and *** significant difference at $P < 0.001$ $P < 0.01$ and $P < 0.05$; [5]Leaf area index; [6]Specific leaf area (SLA) (cm2 g-1) was defined as the one-sided area of a fresh leaf divided by its oven dried mass.

Table 6.3: Comparison of sorghum, cowpea and bottle gourd final biomass yield, yield and harvest index in response to season (2013/14 and 2014/15), cropping system (SS – sole sorghum, SC – sorghum cowpea, SB – sorghum bottle gourd) and water regime (FI – full irrigation, DI – deficit irrigation and RF – rainfed).

Water regime	Season	Cropping system	Sorghum			Cowpea			Bottle gourd		
			B[4]	Y[5]	HI[6]	B	Y	HI	B	Y	HI
			(t ha^{-1})		%	(t ha^{-1})		%	(t ha^{-1})		%
FI[1]	2013/14	Sole crops	3,24	1,1	34	0,99ab	0,24b	19	3,98c	2,78d	71b
		Intercrop: Sorghum - Cowpea	3,23	1,39	43	0,69a	0,09a	10			
		Intercrop: Sorghum-Bottle gourd	2,82	1,23	44				1,53a	0,92b	59b
		Means	3,09c	1,24b	40	0,84	0,17	15	2,76	1,85	65
	2014/15	Sole crops	2,36	0,8	34	4,19d	-	-	3,28c	0,39a	12a
		Intercrop: Sorghum - Cowpea	2,34	0,86	37	1,94bc	-	-			
		Intercrop: Sorghum-Bottle gourd	2,21	1,08	49				1,88ab	0,29a	15a
		Means	2,31a	0,91ab	40	3,07	-	-	2,58	0,34	14
DI	2013/14	Sole crops	3,16	1,19	38	0,51a	0,17b	12	6,36e	4e	62b
		Intercrop: Sorghum - Cowpea	3,02	1,11	37	0,46a	0,05a	13			
		Intercrop: Sorghum-Bottle gourd	2,58	0,86	34				2,29b	1,27c	55b
		Means	2,92c[2]	1,05b	36	0,49	0,11	13	4,33	2,64	59
	2014/15	Sole crops	2,4	0,84	36	4,78d	-	-	5,07d	0,64a	12a
		Intercrop: Sorghum - Cowpea	2,51	0,98	39	2,13c	-	-			
		Intercrop: Sorghum-Bottle gourd	2,52	0,8	33				2,25b	0,31a	14a
		Means	2,48b	0,87a	36	3,46	-	-	3,67	0,48	14
RF	2013/14	Sole crops	2,34	0,94	41	0,59a	0,07a	14	1,67ab	0,78b	48ab
		Intercrop: Sorghum - Cowpea	2,36	0,83	35	0,22a	0,07a	21			
		Intercrop: Sorghum-Bottle gourd	2,39	0,91	37				1,17a	0,49a	41a
		Means	2,36ab	0,89a	38	0,41	0,07	18	1,43	0,64	45
	2014/15	Sole crops	2,81	1,06	38	5,05d	-	-	3,94c	0,62a	17a
		Intercrop: Sorghum - Cowpea	2,43	0,75	31	2,75c	-	-	-	-	-
		Intercrop: Sorghum-Bottle gourd	2,74	1,03	38				2,3b	0,41a	18a
		Means	2,66	0,95a	36	3,91	-	-	3,13	0,52	17
Overall mean			2,64	0,98	32	2,02	0,12	15	2,82	1,08	38
Season			0,05	0.14*[3]	4	0,96	-	-	0,54	0.34*	31*
water			0,06	0,19	6	0,98	0,11	12	0.61*	0,25	21
Intercropping			0,06	0,18	6	0,98	0.08*	21	0,62	0,25	26
Year x water			0.13**	0,21	8	1,24	0,15	19	0,79	0,49	21
Year x intercropping			0,12	0,19	21	1.03**	0,16	11	0.70**	0,42	39
Year x Water x Intercropping			0,13	0,25	32	1,09	0,45	12	0,89	0,35	53
CV%			14,8	25,8	23,4	22,3	13,5	ns	37,6	13,8	13,6

[1] Full irrigation (FI) Deficit irrigation (DI) Rainfed (RF)

6.3.7 Land equivalent ratio

The productivity of the intercrop systems was evaluated using land equivalent ratio (LER) (Fig 6.5). Statistically, there were no significant differences observed for the different intercrop systems between the two growing seasons and even when grown under different water regimes. Average LER across water regimes and cropping systems was 1.45 indicating a 45% increase in productivity compared to sole sorghum. Based on mean values of cropping systems alone, the sorghum - cowpea intercrop had the highest LER (1.54) in comparison to SB (1.44); this was related to the complementary responses observed between sorghum and cowpea (Section 6.3.3 and 6.3.6). Across water regimes, the trend in LER was such that RF (1.61) > FI (1.51) > DI (1.28) (Fig 6.5). Observed LER under RF conditions was associated with low but stable yields of both bottle gourd and cowpea relative to sole and intercrop systems. During 2013/14 growing season, intercrop systems grown under DI resulted in lower LER (38%) relative to 2014/15. Comparing LER of SB across the two growing periods, results showed that average LER was lower (7.68%) in 2013/14 when compared to 2014/15. This was related to improved water availability in 2014/15. On average, intercropping sorghum with cowpea was more productive (10.76%) than intercropping it with bottle gourd.

6.3.8 Water use and water use efficiency

Although not statistically significant, differences in water use were observed across the growing seasons, water regimes and cropping systems. Results showed that mean WU during 2014/15 was higher (50.30%) than during 2013/14 (Table 6.4). This was consistent with water added under each water regime (FI > DI > RF) (Section 6.3.1) and larger canopy size of all cropping systems during the 2014/15 growing season (Fig 6.3 and Table 6.2).

During 2013/14, the trend for WU across water regimes was such that FI (285.91 mm) > DI (210.35 mm) > RF (174.39 mm). Intercropping sorghum with cowpea (SC) and bottle gourd (SB) improved WU (11.45 and 4.42%, respectively) relative to sole sorghum (SS) (Table 6.4). Under FI and DI, intercropping sorghum with cowpea improved WU (12.22 and 25.30%, respectively) relative to SS while a reduction (-1.82 and -14.08%, respectively) was observed under SB relative to SS. Under RF conditions, SB was observed to have the highest overall improvements of WU (29.17%) during 2013/14, in contrast to SS and SC (Table 6.4). This was associated with observed high HI of intercropped bottle gourd relative to intercropped cowpea and sole sorghum under RF conditions.

During 2014/15, similar to 2013/14 the trend in WU across water regimes was such that FI (388.57 mm) > DI (319.12 mm) > RF (290.31 mm). Values of WU were consistent with amount of water added to each water regime (FI > DI > RF) (Section 6.3.1). On average, intercropping resulted in a marginal improvement (2.13%) in WU relative to sole sorghum (SS). Under FI and DI, SB improved WU (1.27 and 22.86%, respectively) relative to SS. On the other hand, intercropping sorghum with cowpea resulted in a reduction in WU across all water regimes [DI (-7.89) > FI (-1.09) > RF (-0.59%)] relative to SS (Table 6.4).

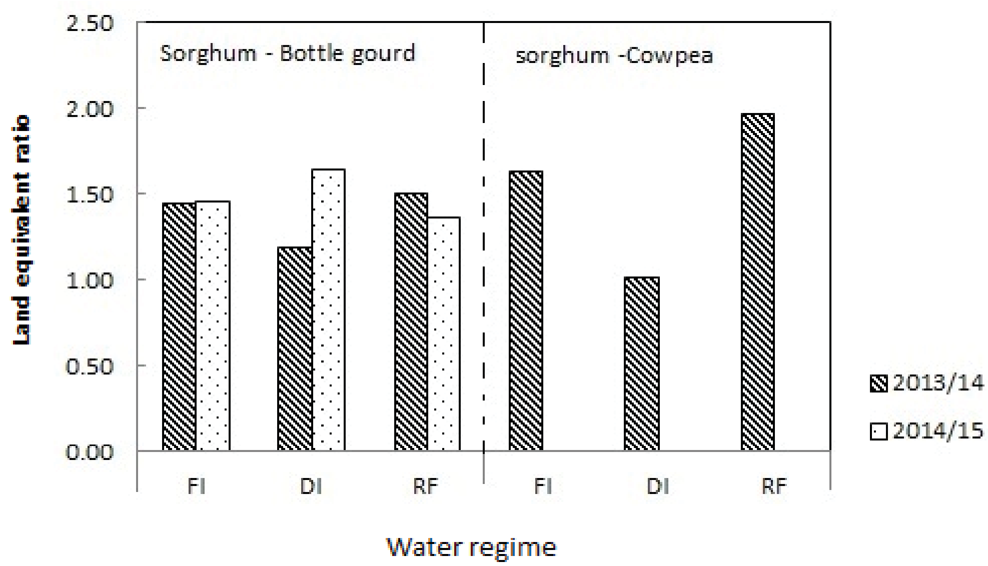

Figure 6.5: Comparison of land equivalent ratio of sorghum – cowpea and sorghum – bottle gourd intercrop systems in response to the different water regimes [full irrigation (FI) deficit irrigation (DI) rainfed conditions (RF)].

Although not statistically significant, WUE calculated based on total biomass (WUE_b) varied across seasons, water regimes and cropping systems. During 2013/14, WUE_b for sorghum was 3.03% lower than what was observed during 2014/15 growing season. The observed trend for sorghum WUE_b across both growing seasons was RF > DI > FI and this was inverse to measured

WU across the water regimes (Table 6.4). Increasing the WU (the denominator) with a fixed biomass (the numerator) reduced WUE_b.

Overall, intercropping (with cowpea and bottle gourd) improved WUE_b of sorghum by an overall 51.63% and 72.2%, for 2013/14 and 2014/15, respectively. This was attributed to improved canopy size (Fig 6.4) and similarities in WU (Table 6.4) of the systems relative to SS. Highest (105.56%) ΔWUE_b was observed under DI conditions relative to RI and FI (Table 6.4) for both growing seasons. This is consistent with either high biomass or low water use by the intercrops (cowpea and bottle gourd) relative to their sole cropping systems.

Though not statistically significant, WUE calculated based on yield (WUE_g) also varied across seasons, water regimes and cropping systems. During the 2013/14 growing season, WUE_g was 35.79% higher than 2014/15 (Table 6.4). During the 2013/14 growing season, the trend observed for sorghum WUE_g across water regimes, was RF (5.89 kg mm^{-1} ha^{-1}) > DI (4.60 kg mm^{-1} ha^{-1}) > FI (3.75 kg mm^{-1} ha^{-1}) while during 2014/15 it was RF (4.72 kg mm^{-1} ha^{-1}) > FI (2.42 kg mm^{-1} ha^{-1}) > DI (2.07 kg mm^{-1} ha^{-1}). It should be noted that under RF conditions, WUE_g was consistently high across the growing seasons. This was attributed to low WU observed under RF conditions relative to DI and FI. Similar to WUE_b, the observed trend for WUE_g for 2013/14 was consistent with WU of sorghum across water regimes.

Overall, intercropping improved WUE_g of sorghum by 62.45% relative to sorghum sole crop (Table 6.4). This was attributed to improved productivity of intercrop systems relative to SS (Fig 6.4). During 2014/15, overall ΔWUE_g by intercropping was 41.46% and this was lower (-27.48%) than what was observed in 2013/14. This was also associated with low WU during 2013/14 relative to 2014/15. Highest ΔWUE_g by intercropping were observed under FI during 2013/14 (73.25%) and under DI during 2014/15 (83.25%) (Table 6.4).

Generally, bottle gourd had high WUE_b (32.23% and 82.16%) and WUE_g (64.52% and 94.37%) relative to sorghum and cowpea, respectively (Table 6.4). This was associated with higher biomass production and yield.

Table 6.4: Comparison of water use and water use efficiency across the different cropping system in response to full irrigation, deficit irrigation and rainfed conditions during 2013/14 and 2014/15 growing season.

		2013/14				2014/15			
Water regime	Cropping system	Water use (mm)	WU[3] improvements (%)	WUE_b[4] kg ha^{-1} mm^{-1}	WUE_g[5] kg ha^{-1} mm^{-1}	Water use (mm)	WU improvements (%)	WUE_b kg ha^{-1} mm^{-1}	WUE_g kg ha^{-1} mm^{-1}
FI[1]	S[2]	293.22		11.05	3.75	331.18		7.56	2.42
	C	251.17		3.94	0.96	418.13		5.60	-
	B	297.17		13.39	10.76	331.18		5.95	7.18
	SC	296.82	12.22	52.14[6]	76.85	391.73	-1.09	59.77	-
	SB	291.17	-1.82	30.93	60.05	404.88	1.27	50.25	12.04
DI	S	258.62		12.22	4.6	405.59		12.50	2.07
	C	185.32		2.75	0.91	359.28		6.15	-
	B	199.22		31.92	24.35	405.59		17.65	2.72
	SC	229.57	25.3	67.26	51.08	323.43	-7.89	70.36	-
	SB	179.02	-14.08	78.38	55.75	319.93	22.86	142.67	84.04
RF	S	159.67		14.66	5.89	224.49		19.18	4.72
	C	177.62		3.32	0.39	295.73		8.12	-
	B	154.57		10.80	5.04	224.49		10.01	1.89
	SC	179.42	-3.18	42.74	31.91	306.28	-0.59	57.10	-
	SB	200.67	29.17	47.35	21.18	297.48	-1.75	32.66	-11.65

[1] Full irrigation (FI) Deficit irrigation (DI) Rainfed (RF); [2] Sole sorghum (S), cowpea (C) and bottle gourd (B), sorghum – cowpea (SC) and sorghum – bottle gourd (SB); [3] Water use; [4] Water use efficiency for biomass production; [5] Water use efficiency for economic yield production; [6] Figures in bold represent improvements (%) of WUE by the intercrop systems

6.4 Discussion

Observed results of SWC (DI>RF>FI) suggest that storage capacity of water of the field was heterogeneous, especially at depths between 0.2 and 0.6 m. Observed results of SWC for the top 0.10 m layer suggest that water was lost primarily through evaporation while plant extraction was predominant at the 0.10 – 0.30 m depths. The high SWC observed at depths of 0.30 – 0.60 m under RF relative to FI could be associated with slope position (5% depression from FI (top) to RF (bottom)) and depth of temporary water table relative to soil surface was closer under RF relative to FI. Under RF, SWC between 0.30 and 0.60 m was consistently approaching saturation in 2013/14 and at saturation in 2014/15. Under FI, the same layer was consistently above FC during 2013/14 and approaching saturation during 2014/15. Observed results are consistent with reports by Perazzolo et al. (2004) who observed high SWC and high water table at the foot of a gentle slope. In terms of water table, it could be that the impermeable soil layer observed at depths around 0.60 m restricted water movement down the soil profile resulting in saturated soils and a temporary water table. Conversely, the higher SWC observed at depths of 0.30 – 0.60 m under DI relative to both FI and RF could suggest the impermeable layer was higher resulting in a higher temporary water table. A thin soil layer relative to water tables are beneficial under low rainfall areas and can substantially improve WUE especially for shallow rooted crops (Mueller et al., 2005). However, during seasons of above normal rainfall such conditions are disadvantageous to crop species sensitive to waterlogging. In such instances, crops like sorghum are ideal, as they are more tolerant to waterlogging.

Observed measurements of SWC in response to intercropping during 2013/14 were associated with an increase in demand for water owing to increased plant population (additive intercrop) relative to sole sorghum (SS). Greater water extraction in the 0.1 – 0.3 m was due to increased root volume resulting in increased effective use of water. On the other hand, under optimum conditions (2014/15 season), intercropping improved SWC relative to SS. It is assumed that the crops (cowpea or bottle gourd) added into sorghum could minimize unproductive losses of water (primarily soil evaporation) and improve its soil water availability. Cowpea and bottle gourd may have modified the microclimate within the canopy such that air movement was minimised resulting in increased humidity and a drop in canopy temperature (Ogindo and Walker, 2005). This would have resulted in a reduction in the demand for water by the immediate atmosphere in and around the canopy thus resulting in low soil evaporation. Similar observations have been made by Ogindo and Walker (2003) and Walker and Ogindo (2003) for maize intercropped with cowpea. In the current study, cowpea and bottle gourd acted as live mulch and aided in conserving soil water content. This could also explain why during

2013/14 improved availability of water under DI and FI conditions was observed within the 0.10 – 0.30 cm layer. Improvement in water availability conferred by intercropping is an ideal trait for regions with low and variable rainfall patterns

The observed association of leaf physiological traits (CCI and g_s) is intrinsically linked with photosynthetic potential of sorghum and its ability to acclimatize. Under limited water, reduction of gs was aimed at minimizing transpirational losses (Chaves et al., 2003); however, this also reduces CO_2 absorption. Under limited water conditions, the observed physiological response (CCI and g_s) of sorghum intercropped with cowpea highlights one of the benefits of cereal-legume intercrop systems. Leguminous crop species fix atmospheric nitrogen into the soil and, when grown together with nitrogen scavengers like cereals, improve availability of soil nitrogen (Eskandari and Ghanbari, 2009). Improved nutrient availability is associated with enhanced root function through increased root growth, which resulted in enhanced soil water capture. As a result, g_s was improved and CCI maintained. These results are consistent with findings by Nielsen and Halvorson (1991) who observed an increase in root function with improved soil nitrogen, improving transpiration and ultimately WUE. Intercropping sorghum with cowpea helped improve its physiological response through effective use of water (Blum, 2009). This is advantageous in low rainfall areas with deep soil profiles.

In the current study, the inconsistent results of RWC for sorghum when intercropped with either bottle gourd or cowpea would suggest facilitative and competitive interactions for water between respective component crops. The observed high RWC when sorghum intercropped with bottle gourd can be associated with an increase in soil water availability conferred by the intercrop bottle gourd. Lower RWC observed when sorghum was intercropped with cowpea could be that sorghum and cowpea roots were extracting water in the same horizon. As such, to a limited extent, bottle gourd and cowpea have facilitative and competitive roles, respectively, when intercropped with sorghum. This could have caused a reduction in the availability of soil water for sorghum relative to sorghum-bottle gourd and sole sorghum causing a reduction in plant water status as reflected by low RWC. Under limited water availability, sorghum is generally able to maintain high RWC primarily through osmotic adjustment (OA) (Dias et al., 2014) (accumulation of osmolytes in response to decreasing SWC). The cost of osmotic adjustment on subsequent growth and productivity is not clearly understood. It is associated with stomata sensitivity and reduced transpirational loss. In non-stressed sorghum plants, RWC ranges between 75 – 92% (Jones and Turner, 1978; Stuart et al., 1985; Netondo et al., 2004), depending on genotype. The fact that observed RWC was within the aforementioned range would suggest that sorghum was not stressed. Nevertheless, to minimize the competitive interaction between sorghum and cowpea, the plant population of cowpea can be reduced to improve RWC of sorghum.

The observed response of sorghum canopy characteristics suggests that sorghum canopy growth was sensitive to water availability. Under limited water supply, reduction in canopy size allows the plant to use water ‘sparingly’ until it completes its life cycle, thus ensuring water use efficiency (Kirkham, 2014). The challenge of this eco-morphological response is that a smaller canopy can lead to increased soil evaporation. In addition, since water losses through transpiration are directly related to exchanges of CO_2, there can be concomitant decreases in CO_2 thus limiting biomass production. Intercropping sorghum with either bottle gourd or cowpea under limited water supply improved canopy size of sorghum through regulating tillering, plant height, leaf number and LAI. Intercropping sorghum with cowpea improved plant height, reduced tiller number but increased overall LAI of sorghum.

The eco-physiological basis of tillering suggests that it will occur under optimum water and nutrient conditions as well as the ratio of red to far red light (R/FR) (Lafarge, 2002). Intercropping sorghum with cowpea resulted in a reduction R/FR down the sorghum canopy. This supressed growth and development of meristems responsible for tillering and encouraged stem etiolation (Yang et al., 2014). Due to improved water availability, and as a means of compensating for suppressed tillers, sorghum responded by increasing LAI. Observations of tillering and improved LAI are consistent with those observed by Krishnareddy et al. (2006) and Kim et al. (2010). Conversely, when sorghum was intercropped with bottle gourd, the observed improvements of tillering and subsequently leaf number and LAI were mainly due to low plant population of bottle gourd in the intercrop. The low plant population ensured that the R/FR was always high while at the same time increased availability of soil water. Improved canopy size under intercropping was in response to improved water availability. This resulted in an increase in transpirational surface of sorghum, therefore increase water use efficiency. For additive intercropping, plant population for the added crop can influence canopy size of the main crop. If morphological similarities exist between crop components, replacement intercropping would be more appropriate under limited water availability.

Results of measured final biomass and yield for the two growing seasons were inconsistent with observations of growth and physiology for the corresponding growing seasons. This was mainly attributed to time of harvest where during 2013/14 harvesting occurred at harvest maturity and at soft dough stage during 2014/15. Early harvesting during the 2014/15 growing season was because of persistent bird and monkey attacks on sorghum panicles. According to Vanderlip (1993), under optimum conditions and at soft dough stage, sorghum seed would be two fifths of final seed mass. If this stands true, yield during 2014/15 could have been 60% higher than what was observed and higher than yield from 2013/14 growing season. This deduction would be consistent with observed results of sorghum growth and physiology. Due to early harvesting in 2014/15, observed grain yield was low resulting in low HI as well as WU and WUE, relative to 2013/14. Sorghum grain is very vulnerable to animal, bird and insect attack. Intercropping with either cowpea or bottle gourd marginally improved WU relative to sole sorghum. Improved WU was due to improved canopy expansion rate, attainment of maximum canopy size and increased root density under intercropping relative to sole sorghum. This increased the proportion of transpiration relative to soil evaporation hence reducing unproductive water losses (Mabhaudhi et al., 2013). These results are consistent with several reports in the literature (Morris and Garrity, 1993; Yang et al., 2011; Fan et al., 2013). Intercropping therefore, increases the effective use of water (Blum, 2009), an advantageous trait under water limited environments. Conversely, WU was associated with water applied rather than observed SWC. This could be attributed to an increase in wetting frequency of the effective rooting depth (0 – 0.30 m). Frequent wetting intervals increase productive (crop transpiration) and unproductive (soil surface evaporation) use of water, thus increase WU. These results are consistent with observations by Mabhaudhi et al. (2013) who observed an increase in WU for bambara groundnut under full irrigation in comparison to production under rainfed conditions. On the other hand, low WU observed under DI and RF conditions could be because of saturated soils. Under saturated and/or waterlogged conditions lack of oxygen results in roots hypoxia or anoxia (Promkhambut et al., 2010). Root hypoxia results in impaired root growth and function resulting in a reduction in water uptake by plants. Sorghum is tolerant to short periods of waterlogging. However, under prolonged exposure Promkhambut et al. (2010) observe a 65 – 78% reduction in transpiration and 69% reduction in LAI. Such a reduction in transpiration and LAI can result in a reduction in WU. To minimize the negative effects of waterlogging caused by high water tables land management strategies such as drainage farrows or raised beds can be employed.

Water use efficiency is an important yield determinant under water stress (Molden et al., 2010). Water use efficiency can be increased by either increasing output with a fixed water input or reducing water input with a fixed output. Observed results of increase in WUE for sorghum biomass (WUE_b) and yield (WUE_g) across water regimes were associated with reduced WU. Under water limited conditions, traits that conferred high WUE were reductions in canopy size, which allowed sorghum to maintain transpiration and RWC as well as biomass and yield production. These results are consistent with those observed by Deng et al. (2006)

and Mabhaudhi et al. (2013) who observed 18 and 40% improvements in WUE under water stress conditions for maize and bambara groundnuts, respectively. Without the additional cost of irrigation, sorghum can be productive in semi-arid and arid areas of the region.

Although intercropping resulted in overall improvements in water use (ΔWUE), observed improvements were inconsistent across growing seasons and water regimes. During 2014/15, ΔWUE was inconsistent with what was observed during 2013/14 growing season and this was mainly attributed to the premature harvesting of the trial. During the 2013/14 growing season, ΔWUE for both biomass and yield were associated with observed HI and WU. Increasing availability of water increased average HI for both intercrop systems. Improved HI can be associated with increased biomass production coupled with increased translocation efficiency, which is often observed under optimum growing conditions (Passioura, 2006). Pereira (1996) who stated that WUEg was the product of HI and WUEb described the association of HI, WUEg and WUE_b. Therefore, agronomic practices that can increase HI would also translate to high WUE in intercrop systems. In water scarce environments where irrigation may not be feasible, farmers can conserve soil water during the fallow period to improve soil water availability during the subsequent growing season.

6.5 Conclusion

Intercropping sorghum with cowpea and bottle gourd did not have any negative effect on growth and yield of sorghum. Under limited water availability, intercropping sorghum with either cowpea or bottle gourd resulted in more of a facilitative than competitive interaction with respect to water availability from a physiological, growth and productivity perspectives. Cowpea and bottle gourd could improve soil water availability by minimizing soil evaporation. In addition, cowpea could improve nutrient availability for sorghum and hence improve root function. This allowed for enhanced soil water capture from the soil profile and hence effective use of water. Physiological parameters (g_s and CCI) proved to be useful indices for evaluating sorghum response to intercropping under limited water availability. However, g_s was only evaluated in one season, hence further research is necessary to substantiate its usefulness. Under RF conditions, intercropping improved overall productivity of sorghum. Intercropping sorghum with cowpea resulted in improvement in WU. Overall, productivity (LER), WU and WUE (biomass and yield) for sorghum-cowpea intercrop system were more stable across both growing seasons. Results for sorghum-cowpea intercrop productivity still need to be substantiated since these are primarily based on the first season’s data only. Under low water availability, intercropping should be recommended as a viable water management strategy. Sorghum–cowpea intercrop system should be recommended to semi–arid regions as it showed both yield stability and high WUE. There is a need for future research on the root-shoot responses of intercropped sorghum to varying levels of water availability, focusing more on root interactions.

References

Ahmadi Mousavi, E., Manochehri Kalantari, K., Jafari, S.R., 2009. Change of some osmolytes accumulation in water-stressed Colza (*Brassica napus* L.) as affected by 24-epibrassinolide. Iran. J. Sci. Technol. Trans. A Sci. 33, 1-11.

Aishah, H.S., Saberi, a. R., Halim, R. a., Zaharah, a. R., 2011. Photosynthetic responses of forage sorghums to salinity and irrigation frequency. J. Food, Agric. Environ. 9, 566–569. doi:10.5897/AJB10.2368

Allen, L.H., Kakani, V.G., Vu, J.C. V, Boote, K.J., 2011. Elevated CO2 increases water use efficiency by sustaining photosynthesis of water-limited maize and sorghum. J. Plant Physiol. 168, 1909–18. doi:10.1016/j.jplph.2011.05.005

Allen, R., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop requirements, Irrigation and Drainage Paper No. 56, FAO. Irrigation and Drainage Paper No. 56, FAO.

Asina, M., Herralde, F. De, 2007. Water relations and vulnerability to embolism are not related: experiments with eight grapevine cultivars. Vitis - J. Grapevine Res. 46, 1 – 6.

Chaves, M.M., Maroco, J.P., Pereira, J.S., 2003. Understanding plant responses to drought—from genes to the whole plant. Funct. Plant Biol. 30, 239–264.

Chaves, M.S., Martinelli, J.A., Wesp-Guterres, C., Graichen, F.A.S., Brammer, S.P., Scagliusi, S.M., da Silva, P.R., Wiethölter, P., Torres, G.A.M., Lau, E.Y., Consoli, L., Chaves, A.L.S., 2013. The importance for food security of maintaining rust resistance in wheat. Food Secur. 5, 157–176. doi:10.1007/s12571-013-0248-x

Coll, L., Cerrudo, A., Rizzalli, R., Monzon, J.P., Andrade, F.H., 2012. Capture and use of water and radiation in summer intercrops in the south-east Pampas of Argentina. Field. Crops. Res. 134, 105–113. doi:http://dx.doi.org/10.1016/j.fcr.2012.05.005

Deng, X.-P.X., Shan, L., Zhang, H., Turner, N.C.N., 2006. Improving agricultural water use efficiency in arid and semiarid areas of China. Agric. Water Manag. 80, 23-40. doi:10.1016/j.agwat.2005.07.021

Dias, M.C., Oliveira, H., Costa, A., Santos, C., 2014. Improving elms performance under drought stress: The pretreatment with abscisic acid. Environ. Exp. Bot. 100, 64–73. doi:10.1016/j.envexpbot.2013.12.013

Du Plessis, J., 2008. Sorghum production manual. Department of Agriculture in cooperation with the ARC-Grain Crops Institute Pretoria, South Africa. http://www.nda.agric.za/docs/Infopaks/FieldCrops_Sorghum.pdf

Eskandari, H., Ghanbari, A., 2009. Intercropping of Maize (*Zea mays*) and Cowpea (*Vigna sinensis*) as Whole-Crop Forage: Effect of Different Planting Pattern on Total Dry Matter Production and Maize Forage Quality 37, 152-155.

Fan, Z., Chai, Q., Huang, G., Yu, A., Huang, P., Yang, C., Tao, Z., Liu, H., 2013. Yield and water consumption characteristics of wheat/maize intercropping with reduced tillage in an Oasis region. Eur. J. Agron. 45, 52–58. doi:http://dx.doi.org/10.1016/j.eja.2012.10.010

Farahani, S.M., Chaichi, M.R., 2012. Effects of Field Treatments on Barley Seed Sensitivity to Organic Seed Sanitation (Hot Water). Res. J. Seed Sci. 5, 96 - 105. doi:10.3923/rjss.2012.96.105

Farré, I., Faci, J.M., 2006. Comparative response of maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) to deficit irrigation in a Mediterranean environment. Agric. Water Manag. 83, 135-143.

Hanjra, M.A., Qureshi, M.E., 2010. Global water crisis and future food security in an era of climate change. Food Policy 35, 365–377. doi:10.1016/j.foodpol.2010.05.006

Jones, M.M., 1978. Osmotic adjustment in leaves of sorghum in response to water deficits. Plant Physiol. 61, 122–126.

Jun, F., Yu, G., Quanjiu, W., Malhi, S.S., Yangyang, L., 2014. Mulching effects on water storage in soil and its depletion by alfalfa in the Loess Plateau of northwestern China. Agric. Water Manag. 138, 10–16. doi:10.1016/j.agwat.2014.02.018

Kim, H.K., Luquet, D., van Oosterom, E., Dingkuhn, M., Hammer, G., 2010. Regulation of tillering in sorghum: genotypic effects. Ann. Bot. 106, 69–78. doi:10.1093/aob/mcq080

Kirkham, M.B., 2014. Principles of Soil and Plant Water Relations, Principles of Soil and Plant Water Relations. Elsevier. Kirkham, M.B (ed), Manhattan, USA doi:10.1016/B978-0-12-420022-7.00027-6

Kizito, F., Sène, M., Dragila, M.I., Lufafa, A., Diedhiou, I., Dossa, E., Cuenca, R., Selker, J., Dick, R.P., 2007. Soil water balance of annual crop–native shrub systems in Senegal's Peanut Basin: The missing link. Agric. Water Manag. 90, 137-148. doi:10.1016/j.agwat.2007.02.015

Krishnareddy, S.R., Stewart, B.A., Payne, W.A., Robinson, C.A., Thomason, R.C., 2006. Tillering in dryland grain sorghum clumps as influenced by light, plant density and geometry. Growth (Lakeland) 162-170.

Lafarge, T.A., 2002. Tillering in Grain Sorghum over a Wide Range of Population Densities: Identification of a Common Hierarchy for Tiller Emergence, Leaf Area Development and Fertility. Ann. Bot. 90, 87–98. doi:10.1093/aob/mcf152

Loutfy, N., El-Tayeb, M., 2012. Changes in the water status and osmotic solute contents in response to drought and salicylic acid treatments in four different cultivars of wheat (*Triticum aestivum*). J. Plant Res. 125, 173 - 184.

Mabhaudhi, T., Modi, A.T., Beletse, Y.G., 2013. Response of taro (*Colocasia esculenta* L. Schott) landraces to varying water regimes under a rainshelter. Agric. Water Manag. 121, 102–112. doi:10.1016/j.agwat.2013.01.009

McMaster, G., Wilhelm, W., 1997. Growing degree-days: one equation, two interpretations. Agric. For. Meteorol. 87, 291–– 300.

Modi, A.T., Mabhaudhi, T., 2013. Water use and drought tolerance of selected traditional and indigenous crops. Final Report of Water Research Commission Project K5/1771//4. WRC Report No. 1771/1/13, ISBN 978-1-4312-0434-2. Water Research Commission. Pretoria, South Africa.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: Between optimism and caution. Agric. Water Manag. 97, 528–535. doi:10.1016/j.agwat.2009.03.023

Morris, R.A., Garrity, D.P., 1993. Resource capture and utilization in intercropping: water. Field. Crops. Res. 34, 303-317.

Muchow, R., Carberry, P., 1990. Phenology and leaf-area development in a tropical grain sorghum. Field. Crops. Res. 23, 221 - 237.

Mueller, L., Behrendt, A., Schalitz, G., Schindler, U., 2005. Above ground biomass and water use efficiency of crops at shallow water tables in a temperate climate. Agric. Water Manag. 75, 117–136. doi:10.1016/j.agwat.2004.12.006

Netondo, G., Onyango, J., Beck, E., 2004. Sorghum and salinity: I. Response of growth, water relations, and ion accumulation to NaCl salinity. Crop Sci. 44, 795 – 805.

Nielsen, D., Halvorson, A., 1991. Nitrogen fertility influence on water stress and yield of winter wheat. Agron. J. 83, 1065- 1070.

Ntombela, Z., 2013. Growth and yield responses of cowpeas (*Vigna unguiculata*) to water stress, MSc Thesis,. University of KwaZulu–Natal, Pietermaritzburg, South Africa.

Ofori, E., Berchie, J.N., Nimako, F.O., 2014. Original Research Article Monitoring of soil moisture regime and water use efficiency under maize cowpea cropping system. Int. J. Curr. Microbiol. Appl. Sci. 3, 837–848

Ogindo, H.O., Walker, S., 2005. Comparison of measured changes in seasonal soil water content by rainfed maize-bean intercrop and component cropping systems in a semi-aridarid region of southern Africa. Phys. Chem. Earth, Parts A/B/C 30, 799-808. doi:10.1016/j.pce.2005.08.023

Ogindo, H.O., Walker, S., 2003. The estimation of soil water extraction by maize-bean intercrop and its sole crop components in a semi-aridarid region. Crop Sci. 6, 430 – 435.

Ortmann, G.F., King, R.P., 2010. Research on agri-food supply chains in Southern Africa involving smallholder farmers: Current status and future possibilities. Agrekon 49, 397–417. doi:10.1080/03031853.2010.526428

Ouda, S. a, El Mesiry, T., Abdallah, E.F., Gaballah, M.S., 2007. Effect of Water Stress on the yield of Soybean and Maize Grown under Different Intercropping Patterns. Aust. J. Basic Appl. Sci. 1, 578–585.

Passioura, J., 2006. Increasing crop productivity when water is scarce—from breeding to field management. Agric. Water Manag. 80, 176 -196.

Perazzolo, L., Bica, A.V.D., Bressani, L.A., Flores, J.A.A., Azambuja, E., Martins, F.B., 2004. Landslides: Evaluation and Stabilization/Glissement de Terrain: Evaluation et Stabilisation, Set of 2 Volumes: Proceedings of the Ninth International Symposium on Landslides, June 28 -July 2, 2004 Rio de Janeiro, Brazil. Taylor & Francis, London.

Pereira, L.S., 1996. Sustainability of Irrigated Agriculture. Springer Netherlands, Dordrecht. doi:10.1007/978-94-015-8700-6.

Promkhambut, A., Younger, A., Polthanee, A., Akkasaeng, C., 2010. Morphological and Physiological Responses of Sorghum (*Sorghum bicolor* L. Moench) to Waterlogging. Asian J. Plant Sci. 9, 183–193.

Rockström, J., Barron, J., Fox, P., 2003. Water Productivity in Rain-fed Agriculture: Challenges and Opportunities for Smallholder Farmers in Drought-prone Tropical Agroecosystems*, in: Water Productivity in Agriculture: Limits and Opportunities for Improvement. pp. 145-162.

Rockström, J., Karlberg, L., Wani, S.P.S., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., Qiang, Z., 2010. Managing water in rainfed agriculture—The need for a paradigm shift. Agric. Water Manag. 97, 543–550. doi:10.1016/j.agwat.2009.09.009

Sani, B.M., Danmowa, N.M., Sani, Y.A., Jaliya, M.M., 2011. Growth , Yield and Water Use Efficiency of Maize-Sorghum Intercrop at Samaru , Northern Guinea Savannah, Nigeria. Eng. Agric. Program. Irrig. 19, 253–259..

Singh, J., Behari, P., 2012. Evapotranspiration and water use efficiency of hybrid napier plus berseem intercropping system under organic and inorganic nutrition. J. Agrometeorol. 14, 130 - 133.

Stuart, B.L., Krieg, D.R., Abernathy, J.R., 1985. Photosynthesis and Stomatal-Conductance Responses of Johnsongrass (*Sorghum halepense*) to Water Stress. Weed Sci. 33, 635 -639.

Taylor, J.R.N., 2003. Overview: Importance of sorghum in Africa, in: Proceedings of AFRIPRO Workshop on the Proteins of Sorghum And Millets: Enhancing Nutritional and Functional Properties for Africa, Pretoria, South Africa.

Tuong, T.P., Bouman, B. a. M., 2003. Water productivity in agriculture: limits and opportunities for improvement. Water Product. Agric. limits Oppor. Improv. 44, 53–67. doi:10.2136/vzj2007.0085br

Van Duivenbooden, N., Pala, M., Studer, C., Bielders, C.L., Beukes, D.J., 2000. Cropping systems and crop complementarity in dryland agriculture to increase soil water use efficiency: a review. NJAS - Wageningen J. Life Sci. 48, 213-236. doi:10.1016/S1573-5214(00)80015-9

Vanderlip, R.L., 1993. How a Sorghum Plant Develops [WWW Document]. Kansas State Univ. URL http://www.ksre.k-state.edu/bookstore/pubs/s3.pdf (accessed 6.30.15).

Walker, S., Ogindo, H.O., 2003. The water budget of rainfed maize and bean intercrop. Phys. Chem. Earth, Parts A/B/C 28, 919-926. doi:10.1016/j.pce.2003.08.018

Willey, R.., 1979. Intercropping-Its importance and research needs.1.Competition and yield advantages. Field. Crops Abstr. 32, 1-10.

Yang, C., Huang, G., Chai, Q., Luo, Z., 2011. Water use and yield of wheat/maize intercropping under alternate irrigation in the oasis field of northwest China. Field. Crops. Res. 124, 426–432. doi:10.1016/j.fcr.2011.07.013

Yang, F., Huang, S., Gao, R., Liu, W., Yong, T., Wang, X., Wu, X., Yang, W., 2014. Growth of soybean seedlings in relay strip intercropping systems in relation to light quantity and red: Far-red ratio. Field . Crops. Res. 155, 245-253.

Zegada-Lizarazu, W., Zatta, A., Monti, A., 2011. Water uptake efficiency and above- and belowground biomass development of sweet sorghum and maize under different water regimes. Plant Soil 351, 47–60. doi:10.1007/s11104-011-0928-2

Zougmore, R., Kambou, F.N., Ouattara, K., Guillobez, S., 2000. Sorghum-cowpea Intercropping: An Effective Technique Against Runoff and Soil Erosion in the Sahel (Saria, Burkina Faso). Arid Soil Res. Rehabil. 14, 329-342. doi:10.1080/08903060050136441

CHAPTER 7

WATER USE AND WATER USE EFFICIENCY OF MAIZE LANDRACE – BAMBARA GROUNDNUT – DRY BEAN INTERCROP SYSTEM

Chimonyo, V.G.P., Modi, A.T. and Mabhaudhi, T.

7.1 Introduction

Maize (*Zea mays* L.) is the staple food crop in South Africa (van Averbeke et al., 2011) and is grown by many smallholder farmers. However, many smallholder farming systems are typified by low maize yields as a result of socio-economic and bio-physical constraints (Ortmann and King, 2010). Among these, water availability has been noted to be the most critical yield-limiting factor (TerAvest et al., 2015). The 2014/15 and 2015/16 drought which was the worst since the start of record keeping in 1901 caused widespread yield losses and crop failure (Meyer et al., 2016) for rainfed maize systems. Smallholder farmers, the majority of whom reside in already marginal areas, were particularly affected. While water stress is the primary limiting factor, it has also been observed that lack of access to improved maize varieties that are best suited to farmers' environments contributes to low yields (Van Averbeke et al., 2011; Van Averbeke and Khosa, 2007; Wenhold et al., 2007). In this regard, maize landraces have been identified as a genetic resource with potential to improve low-input low-output smallholder farmer systems in marginal environments.

Maize landraces can be defined as domesticated, locally adapted and traditional maize varieties that have been developed over hundreds of years, through adaptation to the natural and cultural environment due to natural and farmer selection (Zeven, 1998). Therefore, maize landraces have undergone significant natural and artificial selection making them highly adaptable to harsh environments under which smallholder farmers reside (Aguiriano et al., 2008). Several reports have shown that maize landraces possess heat (Driedonks et al., 2016; Ncube et al., 2011) and drought (Bazargani et al., 2011) tolerance. Although low yielding relative to improved genotypes, yields are generally stable under low resource availability (Hellin et al., 2014). For instance, Oliveira et al. (2013) observed that maize landraces of different provenance were adaptable and stable across different environments in Mexico. Such attributes make maize landraces ideal for sustainable production in low-input low-output systems. However, the fact that they yield less than hybrids under optimal conditions acts as a disincentive for their adoption (Modi and Mabhaudhi 2013) in interventions to improve agricultural productivity and food security, and drive rural development. It has been suggested that lack of knowledge on their agronomy and best management practices could be contributing to their status as underutilised crops (Mabhaudhi 2009). Poor agronomic and water management strategies combined with water stress in poor rainfall areas has been associated with observed low yields (Botha et al., 2015). In this regard, several opportunities exist for increasing water productivity of maize landraces under limited water availability. One such strategy is intercropping maize landraces with legumes.

Intercropping is defined as a traditional form of agriculture were two or more crops are grown on the same piece of land varying in either spatial and/or temporal resolution (Willey, 1979). Under complimentary interactions, intercropping has been observed to increase crop yields per unit area, and overall system yield, with a fixed amount of water entering the system relative to monocropping. This has been attributed to (i) an increase in the efficiency of capture and use of available soil water (Chimonyo, 2016; Mabhaudhi and Modi, 2014), (ii) reduction in unproductive loss of water from bare soil evaporation and runoff (Gao et al., 2013), (iii) increased agro-biodiversity which improves yield stability under varying climatic conditions (Thrupp, 2000), and (iv) increase in overall yield per unit area relative to monocrop systems (Naim et al., 2013). Intercropping maize landraces with legumes could result in improved resource capture, utilisation, and hence improved productivity. Cereal-legume intercrop systems present a sustainable technology that can improve food crop diversity and system stability; thus improving short to long term food and nutrition security (Chikowo et al., 2014). In addition, such intercrop systems can aid in improving soil integrity after several cycles; making the technique ideal for the rehabilitation of degraded soils that characterise smallholder farming lands (Jun et al., 2014; Nduku, 2014; Sujatha and Bhat, 2010; Wang et al., 2014; Wise et al., 2007). Intercropping presents a sustainable coping strategy that could lead to long term adaptation to climate variability and change (Chimonyo et al., 2015).

Despite these positive prospects, the promotion of intercropping, especially with maize landraces systems has been limited within low-input low-output smallholder farming systems in marginal lands. This could be due to limited information quantifying productivity of maize landrace intercrop systems, their water use and subsequent WUE. To ensure successful and sustainable promotion of maize landrace and their legume intercrop systems, these is a need to quantify productivity and resource use efficiencies. In this study, it was hypothesised that intercropping maize with either dry bean (*Phaseolus vulgaris*) or bambara groundnut (*Vigna subterranea* (L.) Verdc.) could improve agricultural output and increase water use efficiency.

The objectives of the study were to (i) quantify productivity of maize – dry bean – bambara groundnut intercrop systems under different water regimes, and (ii) quantify water use and determine water use efficiency of maize – dry bean – bambara groundnut intercrop systems.

7.2 Materials and Methods

7.2.1 Plant material

Three species were used in this study, namely, maize landraces (*Zea mays* L.), dry bean (*Phaseolus vulgaris)* and bambara groundnut (*Vigna subterranea* (L.) Verdc.). The maize landrace was sourced from local farmers in Gqunge, Eastern Cape Province, South Africa. The landrace is an early to medium (90 – 120 days) maturing variety with a yield potential of 3 t ha^{-1} (Mazvimbakupa, 2014). Its plant height has been observed to range from 150 – 180 cm, making it ideal for intercropping. A bambara groundnut landrace was sourced from Pongola, KwaZulu-Natal, South Africa (27.3831° S, 31.6198° E). The landrace is a medium to late (120 – 150 days) maturing variety with a yield potential of 0.5 – 2 t ha^{-1} (Mabhaudhi et al., 2013). Information regarding its use in intercrops is limited. A dry bean variety, Ukulinga, was sourced from McDonald Seeds, Pietermaritzburg, South Africa. Ukulinga is a determinate early to medium (90 – 120 days) maturing variety with a yield potential of about 2 – 5 t ha^{-1}.

7.2.2 Site description

A field trial was conducted at the University of KwaZulu–Natal's Ukulinga Research Farm (29°40'S; 30°24'E; 809 m a.s.l.) during the 2015/16 planting season. Ukulinga Research Farm is classified as semi–arid with 77% of the mean annual rainfall of 750 mm received mostly between the months of October and April. The summer months are warm to hot with an average temperature of 26.5°C while temperatures as low as 8.0°C have been observed during winter (Kunz et al., 2016).

The soils are characterised as predominantly clay to clay–loam soils and are moderately shallow ranging from 0.6 m to 1 m. Based on soil texture, the soil water characteristics (bulk density (g m^{-3}), hygroscopic water content (mm m^{-1}), permanent wilting point (mm m^{-1}), field capacity (mm m^{-1}) total available water (mm m^{-1}), saturation (mm m^{-1}) and hydraulic conductivity (mm hr^{-1}) were all determined using hydraulic properties calculator (http://hydrolab.arsusda.gov/soilwater/Index.htm) (Table 7.1). Results of soil chemical properties showed that the carbon (%) for the top 0.2 m layer was 3.5% while N was 0.35%. From these the initial C:N ratio was calculated as 10.

Table 7.1: Soil water properties at different depths for soil at the experimental site.

Texture	BD[1]	HC[2]	PWP[3]	FC[4]	TAW[5]	SAT[6]	K_{SAT}[7]
	g cm^{-3}	-------------------------	--	mm m^{-1}	--	-------------------------	mm d^{-1}
Clay	1.35	0.33	294	416	152	489	19.70

[1] Bulk density; [2] Hygroscopic moisture content; [3] Permanent wilting point; [4] Field capacity; [5] Total available water; [6] Saturation; [7] Hydraulic conductivity.

7.2.3 Experimental design and layout

The experimental design was a split–plot design with sub-plots laid out in randomised complete blocks within the main plots and replicated three times. The main plot was water regime with two levels (irrigation and rainfed). Sub–plots comprised intercrop combinations, with five intercrop combinations. To ensure good establishment across all the treatments, the trial was established under irrigation. Irrigation was withdrawn at establishment for treatments grown under rainfed conditions. Crop establishment was defined as when 90% of experimental plants had emerged.

Water regimes: There were two water regimes – irrigated and rainfed. Full irrigation involved watering crops up to 100% of maize water requirement for the duration of the trial. Irrigation scheduling was based on crop water requirement calculated from the product of maize crop factors (K_c) (Allen et al., 1998) and Priestley-Taylor (PT) reference evapotranspiration (ET_o) values obtained from an automatic weather station (AWS) located within a 1 km radius from the experimental field. The K_c values for grain maize were K_c initial = 0.30 (25 days), K_c mid = 1.20 (70 days), and K_c end = 0.35 (45 days). The durations in brackets indicate the corresponding periods in days (total of 140) for which the crop factors were applied. Crop water requirement (ET_c) was calculated as described by Allen et al. (1998):

$$ET_c = ET_o * K_c \qquad \text{Equation 7.1}$$

where: ET_c = crop water requirement in mm,

ET_o = reference evapotranspiration in mm, and

K_c = crop factor.

Irrigation scheduling was done weekly (every 7 days) and applied using a sprinkler system. Within the seven-day period and in the event of rainfall, irrigation scheduling was adjusted accordingly. The amount of water applied at each irrigation event amount was recorded using rain gauges randomly placed within the experimental plots. During the growing period, supplementary irrigation applied in the FI treatment was 76 mm and cumulative rainfall was 288.81.

Intercrop treatment: The component crops were maize landraces, bambara groundnut and dry bean. The intercropping treatments were: maize landrace (sole), bambara groundnut (sole), dry bean (sole), maize landrace + bambara groundnut (intercrop) and maize landrace + dry bean (intercrop).

Intercropping systems were designed as additive intercrop systems. Since dominant cropping systems in semi-arid areas are maize-mixed (Cairns et al., 2013), the maize landrace was considered as the main crop and was sown at 100% of its recommended plant population in pure and intercrop stands. Bambara groundnut and dry bean were then “added” to the maize landrace by planting additional rows between rows of maize.

Individual plot sizes for each treatment were an area of 13.5 m^2. All rows were 4.5 m long and inter-row spacing for maize landrace (sole and intercrop treatment) and sole bambara groundnut and sole dry bean was 0.75 m. For the intercrop treatments, rows for intercrops were made in the middle (0.375 m) of maize rows. An in-row spacing of 0.50 m was used for maize. For sole bambara groundnut and dry bean, in-row spacing was 0.30 m. Under intercropping, the in-row spacing was maintained at 0.30 m. Plant populations of the maize landrace, bambara groundnut and dry been were 26 666, 44 444 and 44 444 plants ha^{-1} for both sole and intercrop treatments. The plant population used for maize landrace, the main crop component were based on recommended densities for dryland maize production (Jensen et al., 2003).

7.2.3 Data collection

Climate data: Daily weather data were obtained from an automatic weather station (AWS) located less than 1 km from the experimental field and within Ukulinga Research Farm. The AWS is part of the Agricultural Research Council – Institute for Soil, Climate and Water (ARC–ISCW) network of automatic weather stations. Daily weather parameters that were collected included maximum (T_{max}) and minimum (T_{min}) air temperature (°C), solar radiation (Rad, MJ m^{-2}), rainfall (mm) and PT- ET_o (mm).

Crop growth, physiology and yield: Crop data collected included phenological stages such as times to emergence, end of juvenile stage, end of vegetative stage, floral initiation, flowering, cob/pod formation, grain filling, physiological maturity and harvest maturity. A phenological event was deemed to have occurred when it was observed in at least 50% of experimental plants.

Observations of crop phenology were recorded in calendar days and later converted to thermal time using method 2 as described by McMaster and Wilhelm (1997). Measurements of plant height (PHT), leaf number (LN), leaf area index (LAI), stomatal conductance (g_s), chlorophyll content index (CCI), leaf chlorophyll fluorescence (Fv/Fm) and biomass accumulation were collected on a weekly basis for all component crops. At physiological maturity of the maize landrace, all component crops were harvested. Yield and yield components (cob/pod number per plant, grain number per pod, grain weight per cob/pod, 1000 grain weight, harvest index (HI) and yield) were then determined. The trial was harvested at physiological maturity since monkeys were attacking maize cobs and bambara groundnut pods.

Productivity of the intercrop systems was evaluated using Land Equivalent Ratio (LER) as described by Willey (1979).

$$LER = L_a + L_b = \frac{Y_a}{S_a} + \frac{Y_b}{S_b}$$ Equation 7.2

where: LER = land equivalent ratio, LA and L_b = LERs of component crop *a* (maize), and *b* (dry bean or bambara groundnut), respectively, and Y_a and Y_b represent intercrop yield component crop *a* (maize), and *b* (dry bean or bambara groundnut), respectively, while S_a and S_b are their respective sole.

Water use: Water use (ET) for each treatment was calculated as the residual of a soil water balance:

$$ET = P + I - D - R - \Delta SWC \qquad \text{Equation 7.3}$$

where: ET = evapotranspiration (mm), P = precipitation/rainfall (mm), I = irrigation (mm), D = drainage (mm), R = runoff (mm), and ΔSWC = changes in soil water content (mm). Runoff (R) was assumed to be zero since it was negligible in the plots as they had a slope of less than 5%. Drainage was also considered negligible since the observed impeding layer at 0.6 m restricted downward movement of water beyond the root zone. Another reason for rendering drainage negligible was that the top 0.6 m depth was never observed to be reaching field capacity.

Changes in soil water content (SWC) were measured using a PR2/6 profile probe connected to an HH2 handheld moisture meter (Delta–T, UK). The soil profile at Ukulinga is shallow with an effective rooting depth of 0.60 m (Table 7.1). The PR2/6 profile probe has sensors positioned at 0.10, 0.20, 0.30, 0.40, 0.60 and 1.00 m along the probe. Sensors used in the analysis of SWC where the first five (0.10 – 0.60). Due to small variations that occurred at depths of 0.20 and 0.30 m, and 0.40 and 0.60 m, respectively, results for SWC were only presented for depths of 0.10, 0.30 and 0.60 m. Weekly rainfall (R) was obtained from data obtained from the AWS.

To determine whether intercropping resulted in changes in water use, the following equation suggested by Morris and Garrity (1993) was used:

$$\Delta WU\ (\%) = \left[\left(\frac{WU_{ic}}{P_a WU_{sa} + P_b WU_{sb}}\right) - 1\right] * 100\% \qquad \text{Equation 7.4}$$

where: WU_{ic}, WU_{sa} and WU_{sb} = the water use in intercropping, sole cropping species A and sole cropping species B, respectively, and Pa and Pb are the proportions of species A and B in the intercrop, given by Pa = Da/(Da + Db) with Da and Db being the density in intercropping relative to sole cropping of species A and B, respectively.

Water use efficiency: Water use efficiency was only calculated for the sole treatments since it was not possible to separate water use for each component crop in the intercrop systems. Water use efficiency of sole cropping system was therefore calculated as follows:

$$WUE_{Y/B} = \frac{Y/B}{WU}\left(kg\ mm^{-1}\ ha^{-1}\right) \qquad \text{Equation 7.5}$$

where: WUE = water use efficiency (kg mm^{-1} ha^{-1}) and Y = the economic yield (kg ha^{-1}), B = final biomass (kg $ha^{-1)}$ and ET = the water use (mm).

To determine whether intercropping resulted in changes in water use efficiency the following equation suggested by Morris and Garrity (1993) was used:

$$\Delta WUE\ (\%) = \left(\frac{\frac{Y_{ic}}{WU_{ic}}}{\left(\frac{P_a Y_{sa}}{WU_{sa}}\right) + \left(\frac{P_b Y_{sb}}{WU_{sb}}\right)} - 1 \right) * 100\% \qquad \text{Equation 7.6}$$

where: Yic, Ysa and Ysb = the yields in intercropping and sole cropping of species A and B, respectively.

For interpretation, when ΔWU and ΔWUE are greater than zero, WU and WUE are assumed to be higher in the intercrop system relative to the sole crop.

7.2.4 Agronomic management

Prior to planting, soil samples were obtained from the field trial site and analysed for soil fertility and textural analyses. Based on results of soil fertility analyses, a compound fertiliser with an N:P:K ratio of 2:3:2 (22) was applied to supply 15 kg N ha^{-1}. Fertiliser application was designed to meet the nutritional requirements for maize, the main crop, and was broadcast at planting.

Land preparation involved ploughing, disking and rotovating to achieve fine tilth. Planting was done by hand; planting depth for all crops ranged from 2–3 cm. For maize, rows were opened and seed sown within the rows. Upon full establishment (90% emergence), the maize landrace was thinned to the required spacing; excess seedlings were used for gap filling. Routine weeding was done using hand hoes. Insect pests and animal attacks were scouted for at each visit to the field.

7.2.5 Data analysis

Data collected was subjected to analysis of variance (ANOVA) using GenStat® (Version 16, VSN International, UK) and means of significantly different variables separated using Fisher's unprotected.in GenStat® at the 5% level of significance.

7.3 Results

7.3.1 Weather and soil conditions

7.3.1.1 Weather

Weather data for the growing period was consistent with long-term weather data for Ukulinga (***cf***. Section 7.2.2). Overall, the average maximum temperature was 28.56 ± 5.00°C while the minimum temperature was 16.47 ± 2.24°C. Maximum temperature was 2°C higher than long-term temperature averages of 26.5°C. A total of 29 days had above optimum temperatures (30°C) for the maize landrace growth suggesting higher GDD (°Cd), and this would suggest faster crop development. A total of 12 days, of which five occurred during tasselling stage, were considered extremely hot (> 35°C) days implying temperature stress could have occurred (Fig 7.1).

During the growing period, cumulative rainfall was 288.81 mm and the distribution was positively skewed to the early and mid-growing period. There were 75 days when no rain was recorded out of 107 days (Fig 7.1). During the growing period, there were eight dry spells of which five occurred during the last half. A dry spell was defined as a period of five consecutive days with rainfall of less than 7.5 mm. These results suggest that the possibility of intermittent water stress was observed towards the end of the growing period. Cumulative reference evapotranspiration was 348.27 mm, which indicated a deficit of 59.46 mm from observed rainfall received.

The incidences of storm events were experienced twice during the growing period (24th January and 16th March 2015) and coincided with the early and mid - vegetative growth stage for all three crops hence exposing plants to waterlogging, especially bambara groundnut. A storm event was defined as a rainfall event with an intensity of greater than 25 mm hr^{-1}.

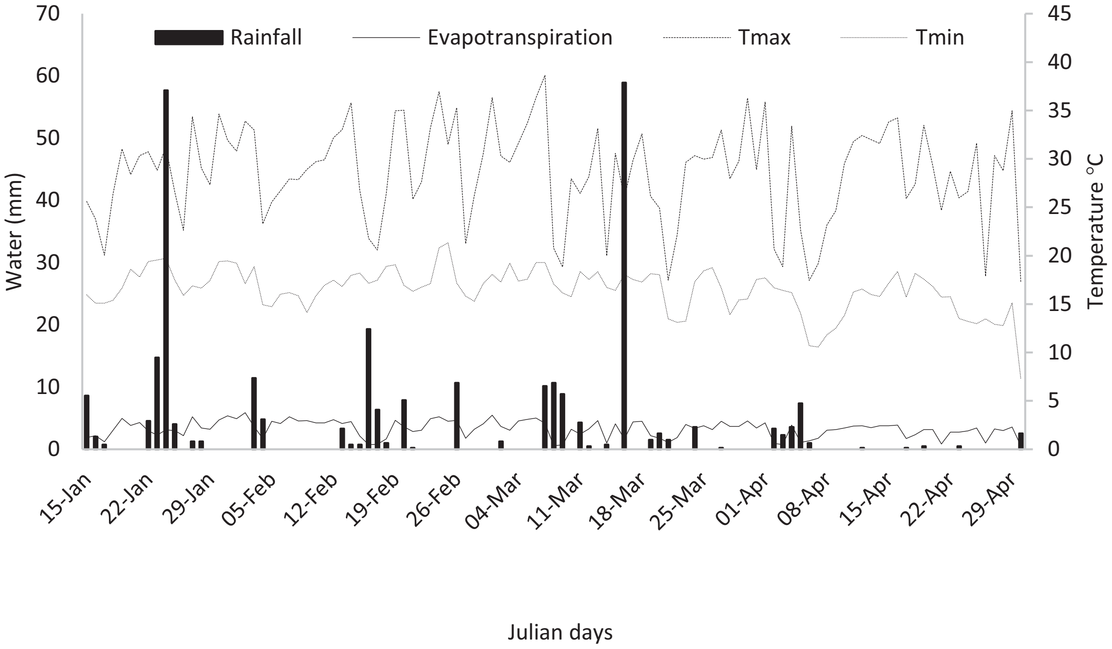

Figure 7.1: Climate data (rainfall, reference evapotranspiration and minimum (Tmin) and maximum (Tmax) temperature) at Ukulinga during the growing period.

7.3.1.2 Soil water

Overall, soil water content (SWC) under irrigated conditions was 10.5% higher and more constant (±5.3) throughout the growing period when compared to rainfed conditions (Fig 7.2). On average, total available water (TAW) under irrigated plots was 41mm ± 71 compared to 18 mm ± 52 under rainfed conditions. Under irrigation, plots of dry bean had the highest TAW (128 mm ± 36) relative to plots of bambara groundnut (85 mm ± 56). When comparing the maize landrace cropping systems under irrigated conditions, it was observed that TAW was 45% higher under intercropping relative to sole maize landrace (Fig 7.2). A similar trend was observed under rainfed conditions; plots with intercropped maize landrace were observed to have higher TAW [maize – bambara groundnut (102 mm ± 42) and maize – dry bean (56 mm ± 56)] relative to those of sole maize landrace with SWC which was observed to by close to or below PWP. Intercropping maize landrace with either dry bean or bambara groundnut improved TAW by 56 and 100%, respectively, relative to sole cropped maize landrace (Fig 7.2).

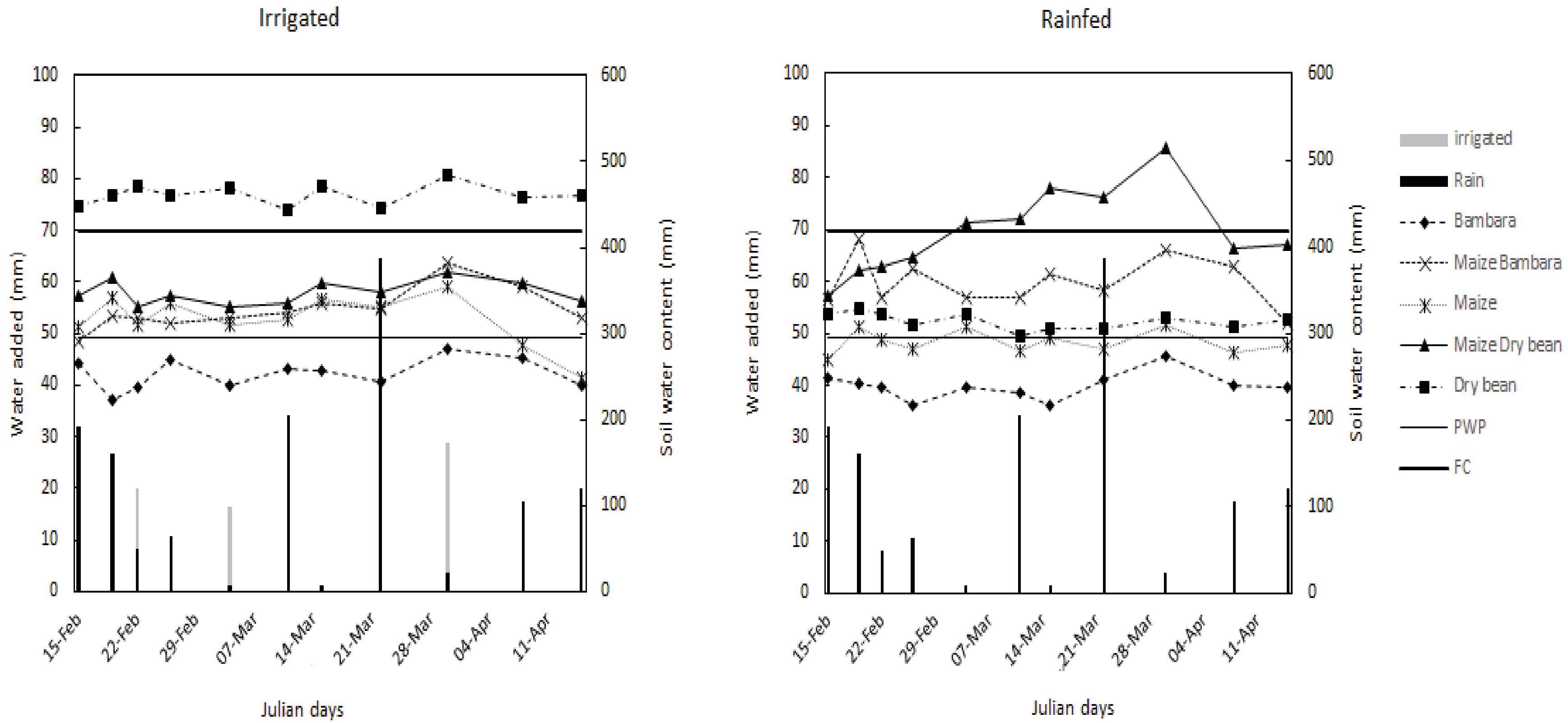

Figure 7.2: Comparison of soil water content within a depth of 1 m in response to cropping systems (Maize, Bambara groundnut, Dry bean, Maize – Bambara groundnut, Maize – Dry bean) and water regimes (Irrigated and Rainfed).

7.3.2 Plant physiology and growth

For maize landrace grown under rainfed conditions, CCI and Fm/Fv were significantly ($P < 0.05$) lower when relative to irrigated conditions (Fig 7.3). This was consistent with the observed trend for TAW. Regardless of water regime, intercropping the maize landrace with dry bean resulted in low CCI and Fm/Fv relative to maize landrace intercropped with bambara groundnuts and sole cropped maize (Fig 7.3). These results are contrary to what was observed for LAI and TAW which were higher for maize landrace intercropped with dry bean relative to the other cropping systems.

Significant ($P < 0.05$) differences were observed for LAI across the maize landrace cropping systems over time. It was observed that, across the water regimes, intercropping maize landrace with either bambara groundnut or dry bean resulted in a significantly higher (31 and 62%, respectively) LAI relative to sole cropped maize landrace (Fig 7.4). This was attributed to the additive nature of the intercrop system where either bambara groundnut or dry bean were added into the maize landrace stand. While there were overall improvements of LAI for maize landrace intercropped with either bambara groundnut or dry bean, intercropping maize landrace with dry bean resulted in a LAI 50% higher than when the maize landrace was intercropped with bambara groundnuts. Results of LAI are consistent with the trend observed for TAW.

Significant ($P < 0.05$) differences were observed for maize landrace g_s under the different cropping systems over time (Fig 7.3). It was observed that, under irrigated conditions maize landrace g_s was high and stable across cropping systems. The observed trend was sole maize (236 mmol m^{-2} s^{-1} ± 56) < maize – bambara groundnut (248 mmol m^{-2} s^{-1} ± 64) < maize – dry bean (252 mmol m^{-2} s^{-1} ± 36). This could be attributed to the higher TAW and increased frequency of wetting interval. Under rainfed conditions, intercropping maize landrace with either bambara groundnut (226 mmol m^{-2} s^{-1}) or dry beans (213 mmol m^{-2} s^{-1}) resulted in significantly higher g_s relative to sole cropped maize (189 mmol m^{-2} s^{-1}). Overall, the observed results of g_s across the maize landrace cropping systems and water regimes were consistent with the observed trends for TAW and LAI. There were no significant differences for maize landrace plant growth parameters [leaf number, plant height and destructive leaf area index (LAI)] in response to cropping system or water regime. It could be that the growth parameters were not as sensitive to water and cropping systems as were physiological parameters.

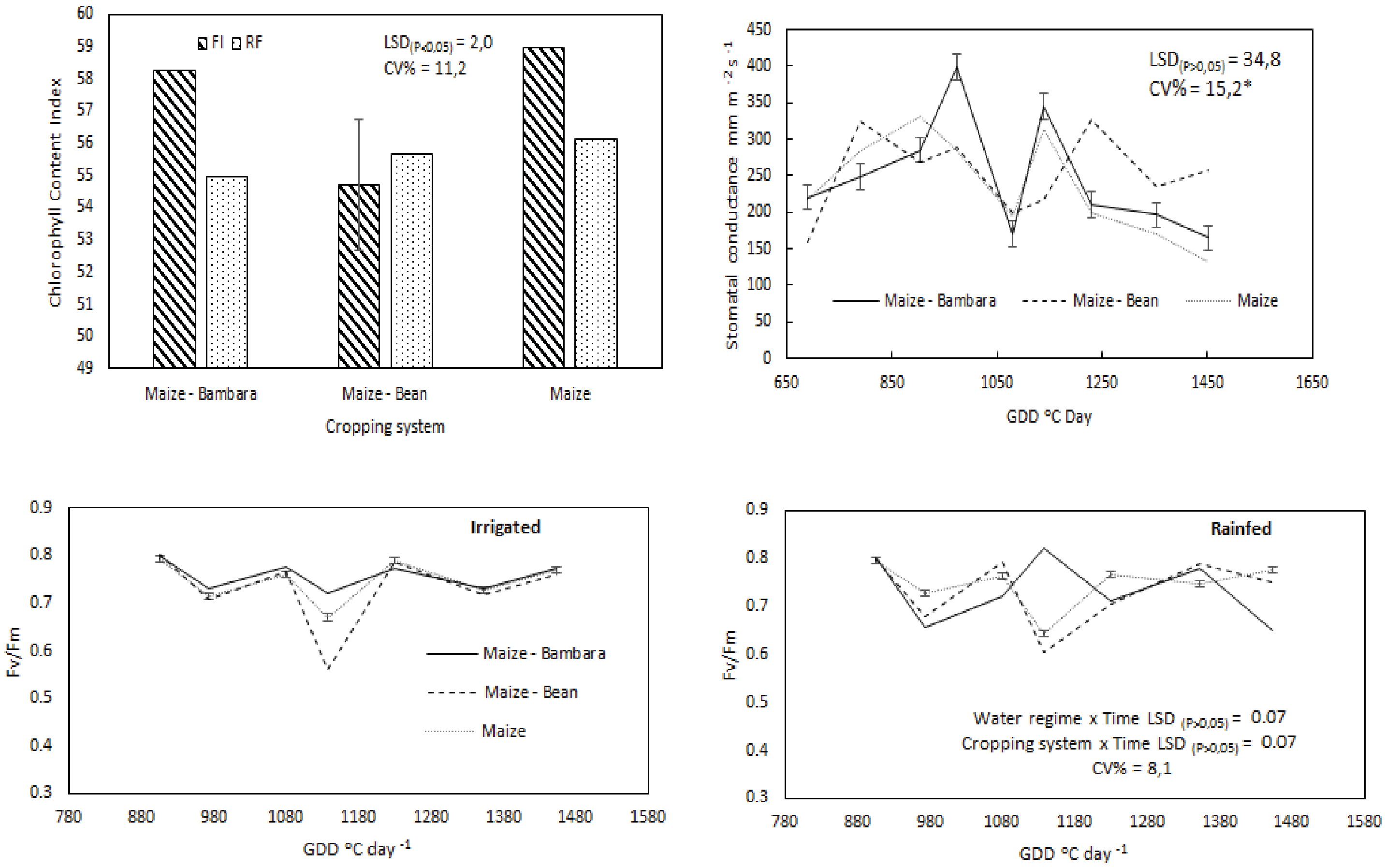

Figure 7.3: Comparison of (i) chlorophyll content index and (ii) stomatal conductance (iii) leaf fluorescence in response to cropping systems (Maize, Bambara groundnut, Dry bean, Maize – Bambara groundnut, Maize – Dry bean) and water regimes (Irrigated and Rainfed).

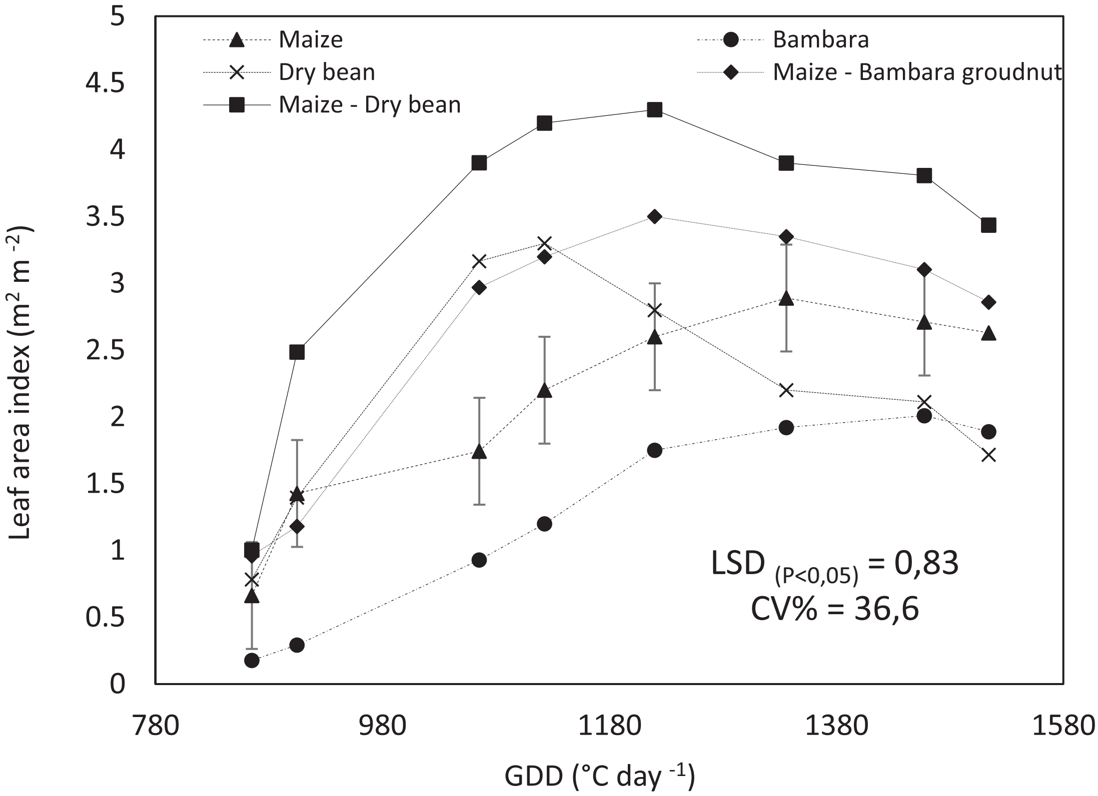

Figure 7.4: Comparison of leaf area index (LAI) for different cropping systems (Sole- maize, bambara groundnut, dry bean, maize - bambara groundnut and maize – dry bean) over time.

7.3.3 Yield and yield components

Water regime and intercropping did not have a significant effect on maize landrace yield (Table 7.2) and this could be related to the insignificant effects on crop growth parameters (leaf number, LAI and PHT). On the other hand, significant ($P< 0.05$) differences were observed for yield and yield component responses to intercrop for the legume species. Despite the improvements in TAW under intercropping, yield of bambara groundnut and dry bean was lower by 41% and 56%, respectively, under intercropping relative to the sole crops.

The productivity of the maize landrace intercrop system was evaluated using land equivalent ratio. Although not statistically significant, results of LER showed that intercropping maize landraces with either bambara groundnut or dry bean resulted in 30% higher overall productivity across water regimes.

Table 7.2: A comparison of biomass yields and harvest index for maize, bambara groundnut and dry bean in response to different cropping (Maize, Bambara groundnut, Dry bean, Maize – Bambara groundnut, Maize – Dry bean) and water regimes (Irrigated and Rainfed).

		Maize (M)			**Bambara groundnut (B)**			**Dry bean (D)**		
Water regime	**Cropping system**	Biomass	Yield	HI	Biomass	Yield	HI	Biomass	Yield	HI
Full irrigation	Sole Systems	2.48	0.83	0.30	1.77	0.45c[1]	0.25	2.86b	1.12bc	0.39
	M + B	2.47	0.87	0.40	0.95	0.15a	0.15	-	-	-
	M + D	2.56	0.72	0.30	-	-	-	1.32a	0.57ab	0.42
Rainfed	Sole Systems	2.51	0.73	0.30	1.67	0.47c	0.29	2.92b	1.27c	0.43
	M + B	2.37	0.82	0.30	1.06	0.23b	0.23	-	-	-
	M + D	2.57	0.79	0.30	-	-	-	1.04a	0.46a	0.45
Mean		2.46	0.80	0.3	1.39	0.32	0.25	2.03	0.86	-
$P_{(value)}$[2]		NS	NS	NS	NS	*	NS	**	*	NS
$LSD_{(P<0.05)}$		-	-	-	-	0.07	-	0.83	0.64	
CV%		-	-	-	-	19	-	24	35	-

[1] Means followed by the same letter indicate that they were not significantly different (p < 0.05) from each other; [2] * and ** significant difference at P < 0.01 and P < 0.05

7.3.4 Water use and water use efficiency

Overall, cropping systems grown under irrigation had higher water use (286 mm) relative to those grown rainfed (210 mm) conditions (Table 7.3). This was consistent with the overall trend for TAW (*cf*. Section 7.3.1.2 and 7.3.2). Under irrigated conditions, differences in WU between the intercropped maize landrace systems and sole cropped maize landrace were nominal (4 mm). Intercropping maize landraces with dry bean improved WU by 7.5% relative to sole cropped maize landraces and dry beans, respectively. A decrease in WU (-1.5%) was observed when the maize landrace was intercropped with bambara groundnut. Observed WU for maize landrace intercropped with dry bean was consistent with trends for TAW, gs and LAI. Observed WU for maize landrace intercropped with bambara groundnut was inconsistent with trends for TAW and g_s.

Under rainfed conditions, intercropping maize landrace with either bambara groundnut or dry bean resulted in lower WU (31 and 11%, respectively) relative to sole cropped maize landrace (Table 7.3). This was inconsistent with observed higher TAW observed for intercropped maize landrace relative to sole cropped maize landrace under rainfed conditions. Intercropping maize landrace with dry bean resulted in the highest improvements in WU of 26% relative to sole cropped maize landrace and dry beans, respectively. This was consistent with observed trends for LAI. Intercropping maize with bambara groundnut resulted in a reduction in WU (-24%) relative to sole cropped component crops. This was similar to what was observed under irrigated conditions.

Overall, water use efficiency was higher (41%) under rainfed conditions than under irrigated conditions. Dry bean had the highest WUE (5.7 kg mm^{-1} ha^{-1}) across all water regimes and this was followed by maize landrace (3.2 kg mm^{-1} ha^{-1}) and bambara groundnut (1.9 kg mm^{-1} ha^{-1}). High WUE observed for dry bean was consistent with results of low WU and higher yields obtained. Intercropping maize landrace with bambara groundnut improved WUE (77%) regardless of water regime. This was attributed to the low WU in the maize – bambara groundnut intercrop systems relative to sole cropped components. On the other hand, intercropping the maize landrace with dry bean resulted in the least improvements of WUE regardless of water regime. This was attributed to the high WU in the maize – dry bean intercrop systems relative to sole cropped components.

Table 7.3: A comparison of water use and water use efficiency across different cropping systems [maize (sole), bambara groundnut (sole), dry bean (sole), maize - bambara groundnut (intercrop) and maize - dry bean (intercrop]) and response to different water regimes.

Water regime	Cropping system	Yield of sole crop (t ha^{-1})	Yield of intercrop (t ha^{-1})	System water use (mm)	Improvements in WU (%)	WUE (kg mm^{-1} ha^{-1})	Improvements of WUE (%)
Irrigation	Bambara groundnut	0.5	–	297	–	1.5	–
	Dry bean	1.1	–	251	–	4.5	–
	Maize	0.9	–	293	–	3.0	–
	Maize – Bambara groundnut	0.8	0.2	291	-1.2	–	66.6
	Maize - Dry bean	0.9	0.5	297	7.5	–	15.8
Rainfed	Bambara groundnut	0.5	–	199	–	2.6	–
	Dry bean	1.3	–	185	–	6.8	–
	Maize	0.9	–	259	–	3.5	–
	Maize – Bambara groundnut	0.7	0.2	179	-24.3	–	86.5
	Maize -Dry bean	0.7	0.6	230	26.6	–	-0.6

7.4 Discussion

Canopy parameters (Leaf number, leaf area, plant height and tiller number) for maize landrace that contribute to LAI were not improved by supplementary irrigation or intercropping. This would suggest that these parameters for this maize landrace were stable across different cropping systems and water regimes. The observed trend for LAI and TAW reflects advantages of intercropping for soil water availability under water-limited conditions. Planting either bambara groundnut or dry bean in-between the maize rows reduced time to maximum canopy cover. As such, the soil was only bare for a short time and the added crop species acted as a live mulch, minimised soil water evaporation, and changed the microclimate in the canopy. It could be that, the intercropped plant species could have created a barrier from wind and solar radiation increasing relative humidity and decreasing canopy and soil surface temperature. This then resulted in a reduction in the evaporative demand for the immediate atmosphere around the canopy; thus, reducing soil evaporation and increasing overall TAW. In this regard, improvements in LAI brought about by intercropping maize landraces with legumes can improve the availability of water for crop use under rainfed cropping systems.

The observed higher g_s, CCI and Fv/Fm for intercropped maize landrace grown under rainfed conditions suggest that intercropping can increase photosynthetic efficiency of maize landrace. Improvements in leaf physiological response for intercropped maize landraces were attributed to improvements in TAW, which were brought about by the observed increase in LAI. Growth and yielding potential of a plant is determined by how efficient it can capture and utilise resources. Under low TAW, similar to what was observed for sole cropped maize landrace, it could be that stomata aperture on the leaf surface of the maize landrace closed to reduce the loss of plant water through transpiration; this in turn reduced g_s and lowered the uptake of CO_2. Prolonged exposure to low TAW could have then resulted in the degradation of chlorophyll and a reduction in Fm/Fv (Lambourn et al., 2007). Under water stress, there is a reduction in the biosynthesis of chlorophyll to accommodate for the down regulation of metabolic process and reduction in photosynthetic reactions (Dalal and Tripathy, 2012). In this regard, the parameters CCI and Fm/Fv can be used to depict the state of photosynthetic apparatus within the leaf. Through the modification of eco-physiology, intercropping can improve photosynthetic efficiency of maize landrace in areas where is it grown under water-limited conditions.

The observed trend for biomass, yield and yield parameter for maize landrace are contrary to observed results of leaf physiology and TAW. It was expected that, the reduction in leaf photosynthetic efficiency because of low g_s, CCI and Fv/Fm would result in a reduction in CO_2

uptake and assimilation, concomitantly, biomass and yield. It could be that the magnitude of reduction for leaf physiology did not have a significant effect on leaf photosynthetic efficiency. It was observed that temperature for this growing season was somewhat higher than the long-term average maximum and minimum temperatures. When plants are grown under well-watered conditions the rate of respiration has been observed to go up under warmer conditions resulting in a reduction in CO_2 assimilates and ultimately biomass (Catoni and Gratani, 2013). It could be that improving TAW for maize landraces also resulted in an increase in photorespiration.

Under water stress conditions, water use efficiency is an important yield determinant (Molden et al., 2010). Water use efficiency can be increased by either increasing output with a fixed water input or reducing water input with a fixed output Observed results in WUE for the different cropping systems and across water regimes were associated with WU. Across the cropping systems grown under the different water regimes, yield for the different component crops was somewhat stable; however, there were differences in WU. These differences were attributed mainly to water availability in the systems and canopy modifications, which in turn increased or reduced WU. Under irrigated condition, wetting intervals for soil surface were more frequent which could have resulted in an increase in bare soil evaporation; thus, resulting in higher WU. Dry bean or bambara groundnuts intercropped with maize landrace acted as a live mulch minimising water use through soil evaporation. The results are consistent with those observed by Chimonyo et al. (2016) who observed 18% reduction in WU under intercropping and improvements in WUE. Without the additional cost of irrigation, maize landraces can be productive in semi-arid and arid areas of the region.

7.5 Conclusion

Intercropping maize with either dry bean or bambara groundnuts did not have any negative effect on growth and productivity of maize landrace. Under limited water availability, intercropping maize with either dry bean or bambara groundnuts resulted in more of a facilitative than competitive interaction with respect to water availability from a physiological, growth and productivity perspectives. Dry bean or bambara groundnuts could improve soil water availability by minimizing soil evaporation since they acted as live mulch. Overall, productivity for maize intercrop systems were more stable across both water regimes. However, under low water availability, maize – bambara groundnut resulted higher improvements in WUE and should be recommended as a viable water management strategy. However, productivity and WUE for the intercrop systems still need to be substantiated since these are primarily based on the first season's data only.

References

Aguiriano, E., Ruiz, M., Fité, R., Carrillo, J.M., 2008. Genetic variation for glutenin and gliadins associated with quality in durum wheat (*Triticum turgidum* L. ssp. turgidum) landraces from Spain. Spanish J. Agric. Res. 6, 599–609.

Akpalu, M., Sarkodie-Addo, J., Akpalu, S., 2012. Effect of Spacing on Growth and Yield of Five Bambara Groundnut (Vigna Subterranea (L) Verdc.) Landraces. J. Sci. Technol. 32, 9–19. doi:10.4314/just.v32i2.2

Bazargani, M.M., Sarhadi, E., Bushehri, A.A.S., Matros, A., Mock, H.P., Naghavi, M.R., Hajihoseini, V., Mardi, M., Hajirezaei, M.R., Moradi, F., Ehdaie, B., Salekdeh, G.H., 2011. A proteomics view on the role of drought-induced senescence and oxidative stress defense in enhanced stem reserves remobilization in wheat. J. Proteomics 74, 1959–1973. doi:10.1016/j.jprot.2011.05.015

Botha, J., Anderson, J., Staden, P. Van, 2015. Rainwater harvesting and conservation tillage increase maize yields in South Africa. Water Resour. Rural ….

Cairns, J.E., Hellin, J., Sonder, K., Araus, J.L., MacRobert, J.F., Thierfelder, C., Prasanna, B.M., 2013. Adapting maize production to climate change in sub-Saharan Africa. Food Secur. 5, 345–360. doi:10.1007/s12571-013-0256-x

Catoni, R., Gratani, L., 2013. Morphological and physiological adaptive traits of Mediterranean narrow endemic plants: The case of Centaurea gymnocarpa (Capraia Island, Italy). Flora - Morphol. Distrib. Funct. Ecol. Plants 208, 174–183. doi:10.1016/j.flora.2013.02.010

Chikowo, R., Zingore, S., Snapp, S., Johnston, A., 2014. Farm typologies, soil fertility variability and nutrient management in smallholder farming in Sub-Saharan Africa. Nutr. Cycl. Agroecosystems 100, 1–18. doi:10.1007/s10705-014-9632-y

Chimonyo, V.G.P., 2016. Quantifying productivity and water use of sorghum intercrop systems. Ph.D. Thesis. University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Chimonyo, V.G.P., Modi, A.T.A.T., Mabhaudhi, T., 2015. Perspective on crop modelling in the management of intercropping systems. Arch. Agron. Soil Sci. 61, 1–19. doi:10.1080/03650340.2015.1017816

Dalal, V.K., Tripathy, B.C., 2012. Modulation of chlorophyll biosynthesis by water stress in rice seedlings during chloroplast biogenesis. Plant. Cell Environ. 35, 1685–703. doi:10.1111/j.1365-3040.2012.02520.x

Driedonks, N., Rieu, I., Vriezen, W.H., 2016. Breeding for plant heat tolerance at vegetative and reproductive stages. Plant Reprod. 29, 67–79. doi:10.1007/s00497-016-0275-9

Gao, Y., Duan, A., Qiu, X., Li, X., Pauline, U., Sun, J., Wang, H., 2013. Modeling evapotranspiration in maize/soybean strip intercropping system with the evaporation and radiation interception by neighboring species model. Agric. Water Manag. 128, 110–119. doi:10.1016/j.agwat.2013.06.020

Hellin, J., Bellon, M.R., Hearne, S.J., 2014. Maize Landraces and Adaptation to Climate Change in Mexico. J. Crop Improv. 28, 484–501. doi:10.1080/15427528.2014.921800

Jensen, J.., Bernhard, R.., Hansen, S., McDonagh, J., Møberg, J.., Nielsen, N.., Nordbo, E., 2003. Productivity in maize based cropping systems under various soil–water–nutrient management strategies in a semi-aridarid, alfisol environment in East Africa. Agric. Water Manag. 59, 217–237. doi:10.1016/S0378-3774(02)00151-8

Jun, F., Yu, G., Quanjiu, W., Malhi, S.S., Yangyang, L., 2014. Mulching effects on water storage in soil and its depletion by alfalfa in the Loess Plateau of northwestern China. Agric. Water Manag. 138, 10–16. doi:10.1016/j.agwat.2014.02.018

Lambourn, L.W., House, C.C., Road, D., England, C.R., 2007. Chlorophyll Fluorescence Analysis for Assessing Water Deficit and Arbuscular Mycorrhizal Fungi (AMF) Inoculation in Cassava (Manihot esculenta Crantz) Formerly of International Institute of Tropical Agriculture (IITA), 1, 108–117.

Mabhaudhi, T., Modi, A.T., 2014. Intercropping Taro and Bambara Groundnut, in: Lichtfouse, E. (Ed.), Sustainable Agriculture Reviews. Springer International Publishing, Cham, pp. 275–290. doi:10.1007/978-3-319-00915-5_9

Mabhaudhi, T., Modi, A.T., Beletse, Y.G.Y.G.Y., 2013. Growth, phenological and yield responses of a bambara groundnut (Vigna subterranea L. Verdc) landrace to imposed water stress: II. Rain shelter conditions. Water SA 39, 191–198. doi:10.4314/wsa.v39i2.2

Mazvimbakupa, F., 2014. Water use characteristics of selected South African maize (Zea mays L.) landraces compared with commercial hybrids. University of KwaZulu-Natal.

McMaster, G., Wilhelm, W., 1997. Growing degree-days: one equation, two interpretations. Agric. For. Meteorol. 87, 291–300.

Meyer, F., Davids, T., Van der Westhuizen, D., Louw, M., Vermeulen, H., 2016. The impact of the drought on South African consumers and the agricultural sector. Oilseeds Focus 2, 26–28.

Naim, A.M. El, Kilali, B.A., Hassan, A.E., Ahmed, M.F., 2013. Agronomic Evaluation of Sorghum and Cowpea Intercropped at Different Spatial Arrangements. J. Renew. Agric. 1, 11–16. doi:10.12966/jra.05.01.2013

Ncube, B., Finnie, J.F., Van Staden, J., 2011. Seasonal variation in antimicrobial and phytochemical properties of frequently used medicinal bulbous plants from South Africa. South African J. Bot. 77, 387–396. doi:10.1016/j.sajb.2010.10.004

Nduku, H., 2014. Crop Performance and Soil Nutrient Dynamics under Different Organic Based Cropping Systems and Modeling The Effect of Climate Change On Maize (Zea May). University of Nairobi.

Oliveira, R.B.R. de, Moreira, R.M.P., Ferreira, J.M., 2013. Adaptability and stability of maize landrace varieties. Semin. Ciências Agrárias 34, 2555. doi:10.5433/1679-0359.2013v34n6p2555

Ortmann, G.F., King, R.P., 2010. Research on agri-food supply chains in Southern Africa involving smallholder farmers: Current status and future possibilities. Agrekon 49, 397–417. doi:10.1080/03031853.2010.526428

Sujatha, S., Bhat, R., 2010. Response of vanilla (Vanilla planifolia A.) intercropped in arecanut to irrigation and nutrition in humid tropics of India. Agric. Water Manag. 97, 988–994. doi:10.1016/j.agwat.2010.01.031

Thrupp, L. a, 2000. Linking agricultural biodiversity and food security: the valuable role of agrobiodiversity for sustainable agriculture. Int. Aff. 76, 265–281. doi:10.1111/1468-2346.00133

Van Averbeke, W., Denison, J., Mnkeni, P., 2011. Smallholder irrigation schemes in South Africa: A review of knowledge generated by the Water Research Commission. Water SA 37, 797–808. doi:10.4314/wsa.v37i5.17

Van Averbeke, W., Khosa, T.B., 2007. The contribution of smallholder agriculture to the nutrition of rural households in a semi-aridarid environment in South Africa, in: Water SA. pp. 413–418. doi:10.4314/wsa.v33i3.49158

Wang, Z.-G., Jin, X., Bao, X.-G., Li, X.-F., Zhao, J.-H., Sun, J.-H., Christie, P., Li, L., 2014. Intercropping enhances productivity and maintains the most soil fertility properties relative to sole cropping. PLoS One 9, e113984. doi:10.1371/journal.pone.0113984

Wenhold, F., Faber, M., Averbeke, W. Van, Oelofse, A., Jaarsveld, P.. Van, Jansen van Rensburg, W., van Heerden, I., Slabbert, R., 2007. Linking smallholder agriculture and water to household food security and nutrition. WaterSA 33, 327–336.

Willey, R.., 1979. Intercropping-Its importance and research needs.1.Competition and yield advantages. F. Crop Abstr. 32, 1–10.

Wise, R., Cacho, O., Hean, R., 2007. Fertilizer effects on the sustainability and profitability of agroforestry in the presence of carbon payments. Environ. Model. Softw. 22, 1372–1381. doi:10.1016/j.envsoft.2006.10.002

Zeven, A., 1998. Landraces: a review of definitions and classifications. Euphytica.

CHAPTER 8

CALIBRATION AND TESTING OF AQUACROP FOR SELECTED SORGHUM GENOTYPES

Hadebe, S.T., Modi, A.T. and Mabhaudhi, T.

8.1 Introduction

High seasonal rainfall variability, delays in onset and irregular distribution of rainfall, and occasional dry spells within seasons negatively impact cereal yields and household livelihoods in sub–Saharan Africa (SSA) (Fjelde and von Uexkull, 2012). The impact is exacerbated under rainfed agriculture, where rainfall is the sole water input into the agriculture system. Variability in rainfall affects timing and location of planting, as onset, cessation and amount of rainfall affect farmers' planting decisions. Cereal crops are a major contributor to food security and economy in arid and semi–arid regions. In SSA, a region where 95% of agriculture is rainfed (Singh et al., 2011), and arid and semi–arid areas account for 43% of total area (Food and Agriculture Organization [FAO], 2008), rainfall is a major limitation to cereal yields. Sorghum is predominantly grown in semi–arid and arid agro–ecologies of SSA, under rainfed conditions. This makes sorghum production highly susceptible to rainfall amount and distribution.

Examining yield response to rainfall amount and distribution under rainfed environments is both laborious and expensive. In consideration of such limitations, the use of crop models is useful. Crop models are valuable prediction tools where environments, soils, genotypes and climatic conditions vary. For increased accuracy of model predictions, models must be parameterized, calibrated and tested before use. For model calibration, one changes model parameters and even coding to obtain accurate prediction versus observed data. On the other hand, testing is the process whereby the model is run against independent data, without any modification of model parameters or code. AquaCrop is a crop water productivity model developed by the Land and Water Division of FAO that simulates crop yield response to water (Raes et al., 2009b; Steduto et al., 2009). AquaCrop predicts crop productivity, water requirement, and water use efficiency and is particularly suited to address conditions where water is a key limiting factor in crop production.

Application of models by non–research end users (farmers, policy makers and extension services) remains a key challenge as models usually require extensive and difficult to obtain data sets for calibration (Hoogenboom et al., 2012). A major distinguishing feature of

AquaCrop is its simplicity, the ability to use minimum data inputs during calibration to produce reliable estimates of crop growth and yield response to water availability (Raes et al., 2009b; Steduto et al., 2009). This procedure is termed 'minimum data input calibration'. It requires a relatively low number of intuitive, easy to obtain parameters and can be used when a crop has previously been calibrated for AquaCrop (Hsiao et al., 2012). The use of the minimum data input for calibration was an attempt to improve uptake and use of crop models in mostly developing countries where access to extensive data sets is limited.

AquaCrop has been parameterized and tested for a wide range of crops (Farahani et al., 2009; Geerts et al., 2009; Hsiao et al., 2009; Karunaratne et al., 2011; Steduto et al., 2009) under different environmental conditions illustrating that the model could accurately simulate yield response to water. AquaCrop has already been parameterized for sorghum using data from Bushland, Texas field trials in 1993 (FAO, 2012). However, there is a need to perform a local calibration for sorghum genotypes under production in SSA. This study aimed to calibrate and test AquaCrop for hybrid, open–pollinated and landrace sorghum genotypes. In this study, the minimum data input calibration procedure was used to calibrate sorghum genotypes, and subsequently test model performance under variable climatic conditions. In part, this study aimed to investigate whether minimum data input calibration (Hsiao et al., 2012) proposed for non–research AquaCrop users was sufficient in predictions of sorghum yield response to water. To our knowledge, no published materials exists on the effectiveness of minimum data input calibration, which makes this a first known study to do so. The choice of genotypes used is explained in the materials and methods section.

8.2 Materials and Methods

8.2.1 Model description

The FAO AquaCrop crop model is a water-driven simulation model (generic crop water productivity model) (Raes et al., 2009a; Steduto et al., 2009). It requires relatively few input parameters to simulate yield response to water of major field and vegetable crops. Its parameters are explicit and mostly intuitive and the model maintains sufficient balance between accuracy, simplicity and robustness (Raes et al., 2009a; Steduto et al., 2009).

The features that distinguish AquaCrop from other crop models are its focus on water, the use of ground canopy cover instead of leaf area index, and the use of water productivity values normalized for climate (atmospheric evaporative demand and of carbon dioxide concentration). This confers the model an extended extrapolation capacity to diverse locations and seasons

(Steduto et al., 2007), including future climate scenarios. The model uses canopy ground cover (CC) instead of leaf area index (LAI) as the basis to calculate transpiration and to separate soil evaporation from transpiration. Biomass is then calculated as the product of transpiration and a water productivity parameter (Equation 8.1).

$$\mathbf{B = WP \ x \sum Tr} \qquad \text{Equation 8.1}$$

where: B = aboveground biomass (ton/ha),

WP = water productivity (biomass per unit of cumulative transpiration), and

Tr = crop transpiration.

Crop yield is then calculated as the product of aboveground dry biomass and harvest index (HI):

$$\mathbf{Y = B \ x \ HI} \qquad \text{Equation 8.2}$$

where: Y = crop yield,

HI = harvest index.

Although the model is simple, it gives attention to the fundamental processes involved in crop productivity and in the responses to water, from a physiological and agronomic perspective (Raes et al., 2009a). The FAO AquaCrop model predicts crop productivity, water requirement, and water use efficiency under water-limiting conditions (Raes et al., 2009a). AquaCrop considers the soil, with its water balance; the plant, with its development, growth and yield processes; and the atmosphere, with its thermal regime, rainfall, evaporative demand and carbon dioxide concentration.

Minimum data input calibration requires a relatively low number of parameters compared to full calibration, and is used when a crop has previously been calibrated for AquaCrop. These are intuitive input variables, either widely used or largely requiring simple methods for their determination. Minimum input data consists of weather data, crop and soil characteristics, and management practices that define the environment in which the crop was cultivated and are described in Hsiao et al. (2012). In this study, user defined model inputs were used to describe soil physical and hydraulic properties, daily weather, and user specific crop parameters for each sorghum genotype obtained from field trials were used to describe crop growth and development. The crop description parameters (Table 8.2) were taken from Hsiao et al. (2012) where minimum data sets required for calibration were described. Additionally, the model also considers some management aspects such as irrigation and fertility, as they affect the soil water balance, crop development and therefore final yield. Pests, diseases, and weeds are not considered (Raes et al., 2009b).

8.2.2 Plant material

Three sorghum genotypes, a hybrid (PAN8816), an open-pollinated variety (Macia) and a landrace (Ujiba), were selected for this study. This reflected the range of germplasm typically used by farmers for sorghum production in southern Africa. PAN8816 and Ujiba are grown in South Africa in sorghum growing regions. Macia, was developed by the International Crop Research Institute for the Semi–Arid Tropics (ICRISAT), and is produced in most sorghum growing regions across SSA (Charyulu et al., 2014; Takele and Farrant, 2013). Additional information on genotype characterisation is as defined in Table 8.1.

Table 8.1: Seed, growth and development characteristics of three sorghum genotypes used in this study.

Characteristics	Genotype		
	PAN8816	**Macia**	**Ujiba**
Source	Pannar Seeds®, seed company	Capstone®, seed company	Smallholder farmers in Tugela Ferry, South Africa (28°44'S, 30°27'E)
Cultivar Type	Hybrid	Open–pollinated variety	Landrace
Seed colour	Bronze	White/ Cream white	Dark brown
Tannin content	Low	Low	High
Bird proof tolerance	Low	Low	High
Maturity characteristics	Medium–late maturing	Early–medium maturing	Medium–late maturing
Height	Semi–dwarf (1.3–1.5 m)	Semi–dwarf (1.3–1.5 m)	Tall (1.5–2 m)
Farmer group preference	Commercial farmers	Commercial and smallholder farmers	Smallholder farmers

8.2.3 Site description

Field trials were planted at Ukulinga Research Farm (30°24'S, 29°24'E, 805 m a.s.l) over two planting seasons (2013/14 and 2014/15). The farm is situated in Pietermaritzburg in the subtropical hinterland of KwaZulu-Natal province and represents a semi-arid environment characterized by clay-loam soils (USDA taxonomic system). Rain falls mostly in summer, between September and April. Rainfall distribution varies during the growing season (Swemmer et al., 2007) with the bulk of rain falling in November, December and early January. Occasionally light to moderate frost occurs in winter (May – July).

8.2.4 Trial layout and design

Field trials planted at Ukulinga on 17 January during the 2013/14 planting season were used for model calibration. The experimental design used was a randomized complete block design with three replications. Independent field trials planted during the 2014/15 planting season were used to test model performance. The experimental design was a split–plot design with planting date as the main factor and genotypes as the sub–factor laid out in randomised complete blocks with three replications. The planting dates (03 November 2014, 17 November 2014, and 26 January 2015) represented early, optimal and late planting dates for sorghum. Early planting reflected onset of rainfall at Ukulinga in 2014/15 season. The early planting date can be defined as the first rainfall event capable of supporting germination. In this study, the early planting date was defined according to the Agricultural Research and Extension (AREX) criterion (Raes et al., 2004) which defines a planting date as the occurrence of 25 mm rainfall in 7 days before planting. This ensures there is enough soil water, not only for germination but also to sustain the crop through the early development stage (Moeletsi and Walker, 2012). Optimal planting date was based on Department of Agriculture, Forestry and Fisheries (DAFF) (2010) recommendations and historical weather data at Ukulinga. Late planting date represented latest planting from which seasonal rainfall can sustain 120–140 day growing season (Table 8.3). This was determined from historical weather data, where onset of winter season and cessation of rainfall usually occurs in May at Ukulinga.

All trials comprised three sorghum cultivars, namely: PAN8816, Macia and Ujiba. The trials measured 310 m^2, with individual plot size of 6 m * 4.5 m (18 m^2), with 1 m interplot spacing between the plots. Final inter-row spacing was 0.75 m with 0.30 m intra-row spacing, amounting to 21 plants per row and 63 experimental plants per plot. Each individual plot had seven rows with the three inner most rows as the experimental plants, and the remaining rows reserved for destructive sampling.

8.2.5 Agronomic practices

Soil samples were collected and analysed for fertility before land preparation. Before planting, fallow land was mechanically ploughed, disked and rotovated. A pre-emergence herbicide, Round-up® (glyphosate at 10 ml per litre of water) was applied to control weeds two weeks before planting. A deficit of fertilizer requirements (Smith, 2006) was applied using Gromor Accelerator® (30 g kg^{-1} N, 15 g kg^{-1} P and 15 g kg^{-1} K), a slow release organic fertilizer at 14 days after sowing (DAS). Planting rows were opened by hand 25 mm deep and seeds were hand-sown in the ground. Planting was conducted by drilling sorghum seeds. Thereafter, at crop establishment (14 DAS), seedlings were thinned to the required spacing. Scouting for pests and diseases was done weekly. Cypermethrin® (15 mℓ per 10 ℓ knapsack) was applied to control insect pests one month after planting. Weeding was done using hand-hoes at frequent intervals.

8.2.6 Input data

8.2.6.1 Soil

Important soil input parameters required by AquaCrop model are: soil texture, volumetric water content at field capacity (FC), at permanent wilting point (PWP), and at saturation (SAT), saturated hydraulic conductivity (Ksat), and soil thickness (depth of soil profile). The soil textural class was described as clay (USDA Taxonomic System). Soil physical and hydraulic properties were obtained from classification and characterisation of experimental site soils by Mabhaudhi (2012). Soil hydraulic and physical properties were used to develop a soil (.SOL) file in the model. The soil was classified as clay, with 0.6 m soil depth. Other values used to describe the soil file were: PWP = 28.3%, FC = 40.6%, SAT = 48.1%, TAW = 123.0 mm m^{-1}, and Ksat = 25.0 mm d^{-1}.

8.2.6.2 Meteorological data

The climate file in AquaCrop is defined using maximum temperature (°C), minimum temperature (°C), rainfall (mm) and reference evapotranspiration (mm). Meteorological data for Ukulinga was obtained from an automatic weather station (within 100 m radius) courtesy of the Agricultural Research Council – Institute for Soil, Climate and Water (ARC–ISCW). Reference evapotranspiration was obtained from the weather station and was based on the FAO Penman-Monteith equation from full daily weather data sets, as described by Allen et al. (1998). Carbon dioxide concentration was obtained from AquaCrop's default Maunalua file. Daily meteorological data from 01 January 2014 until 31 August 2015 was used to develop the climate (CLI) file in the model.

8.2.6.3 Crop growth and development parameters

Crop parameters were used to calibrate AquaCrop's default sorghum file (Raes, Steduto, Hsiao, and Fereres, 2012) for the three sorghum genotypes as part of the minimum data input calibration procedure. The minimum data input procedure includes providing input data for the following: planting date, planting density, time to crop establishment, time to flowering, flowering duration, maximum canopy cover, time to maximum canopy cover, time to senescence, time to physiological maturity, and harvest index (Table 8.2). The minimum data input calibration procedure includes rooting depth. However, in this study, we used the default depth in the default sorghum file.

Planting density was calculated as number of plants per given area based on row spacing and plant spacing. Area measurements were converted from m^2 to hectares and planting density was reported in plants/ ha. Time taken to reach phenological stages was recorded in days as when ≥50% of planting population exhibited diagnostic signs of that particular stage. Canopy cover was measured using the LAI2200 canopy analyser (Li–Cor®, USA) at midday (12 am – 2 pm), and calculated as described by Mabhaudhi et al. (2014). Maximum canopy cover was recorded as the highest recorded canopy cover measurement over the growing season. Time to maximum canopy cover was taken as time from sowing to when maximum canopy cover was observed for each genotype. Flowering duration described time from when at least half the experimental population exhibited flower inflorescence to time when at least half the experimental population exhibited anthesis.

To quantify effective rooting depth, an area around a plant root zone was dug out 1 m deep and 0.5 m from the main stem at physiological maturity. After which, the soil around the roots was brushed off, and root length was measured from exposed roots. The model can simulate the presence of an impeding layer. Soil profiling at the experimental site revealed that the effective rooting depth of the soil was 0.6 m, which was input into the soil file. While for the crop, it was maintained as the default 2 m. During model runs, the depth of the soil profile will limit root growth, while the value of 2 m represents the crop's potential in the absence of an impeding layer or a shallow soil. This feature allows then for the same crop file to be used for different soils without the need to change the crops' effective rooting depth whenever the soil file is changed. Soil water content was measured weekly using a PR2/6 profile probe (Delta–T, UK), and used test model estimation of soil moisture.

Table 8.2: User–specific crop parameters used in minimum data input calibration of three sorghum genotypes (PAN8816, Ujiba and Macia) plus the original AquaCrop default sorghum crop file values.

Parameter	Genotype			
	PAN8816	**Ujiba**	**Macia**	**Default sorghum crop file**
Planting date	17 January 2014	17 January 2014	17 January 2014	
Planting density (plants/ ha)	44 444	44 444	44 444	44 444
Time to crop establishment (days)	14	14	14	14
Maximum canopy cover (%)	89.1	80.3	80.3	89
Time to maximum canopy cover (%)	70	77	84	84
Time to flowering (days)	70	77	79	70
Duration of flowering (days)	14	14	14	27
Time to canopy senescence (days)	126	126	126	98
Time to physiological maturity (days)	140	140	140	140

Flowering was observed as time taken for 50% of experimental plant population to panicle bloom. Duration of flowering was recorded as time taken from flowering to when 50% of experimental population exhibited anthesis. Physiological maturity was observed when a dark spot appeared on the opposite side of the kernel from the embryo signalling completion of dry matter accumulation. However, physiological maturity in model simulations was observed when dry matter accumulation (biomass and yield) ceased. Since all trials were under sub–optimal rainfall, reference harvest index could not be calculated for sorghum genotypes. Therefore, the default harvest index was used for all genotypes. Crop growth and development parameters were specified as inputs in genotype crop (.CRO) in the model.

8.2.7 Model calibration

Observations from field trials planted at Ukulinga on 17 January during the 2013/14 were used to calibrate each of the three sorghum genotypes. Minimum data input calibration was used, using parameters outlined in Table 8. 2. Simulations were performed with the AquaCrop model (Version 4.0) as described by Raes et al. (2009a) and Steduto et al. (2009). Key inputs in the model included: climate file, soil file, and crop files (three crop files, one file per genotype, which were calibrated using minimum data input calibration). Calibration of the model was conducted using 2013/14 data from rainfed trials conducted at Ukulinga. since AquaCrop is a canopy level model where biomass and yield are calculated based on transpired water from the canopy, simulated canopy cover values were first to be matched to observed values. Upon good agreement between simulated and observed canopy cover, agreement in soil water content, biomass, yield and harvest index were then compared. Data used for calibration were not used for testing.

8.2.8 Model testing

Testing is an important step of model verification. It involves a comparison between independent field measurements (data) and simulated output created by the model. Testing confirms whether results obtained from the model can be relied on and if they compare well with experimental results. Model testing in this study was done by comparing canopy cover, biomass, yield and harvest index simulated by the model and those from the observed field experiments planted at different planting dates during the 2014/15 season.

8.2.9 Statistical analysis

Different statistical indices including coefficient of determination (R^2), root mean square error (RMSE) and its systematic ($RMSE_S$) and unsystematic components ($RMSE_U$) as well as the index of agreement (*d–index*) were used for comparison of simulated against observed data. Systematic RMSE was calculated (Loague and Green, 1991) as follows:

$$\mathbf{RMSE} = \left[\frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I}(P_j^i - O_j^i)^2\right]^{0.5} \qquad \text{Equation 8.3}$$

where: n is the number of observations, P_i and O_i refer to simulated and observed values of the study variables, respectively. The RMSE is a good overall measure of model performance. It indicates the absolute fit of a model to observed field data, and evaluates the closeness between the two values. The RMSE was normalized by expressing it as a percentage of data range to remove scale dependency. The simulation is considered excellent with a normalized RMSE less than 10%, good if the normalized RMSE is greater than 10% and less than 20%, fair if normalized RMSE is greater than 20 and less than 30%, and poor if the normalized RMSE is greater than 30% (Jamieson et al., 1991).

Systematic Root Mean Square Error ($RMSE_S$) was calculated as the square root of the mean squared difference in regressed prediction-observation pairings within a given analysis region and for a given period (Loague and Green, 1991).

$$\mathbf{RMSE_s} = \left[\frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I}(\widehat{P}_j^i - O_j^i)^2\right]^{0.5}$$ Equation 8.4

where: P^i_j is the individual predicted quantity at site i and time j, P^ is the least square aggression, O^i_j is the individual quantity at site *i* and time *j*, and the summations are over all sites (*I*) and over time periods (*J*) and the least square aggression (P^) is:

$$\widehat{P} = a + b\, O_j^i$$ Equation 8.5

where: *a* is the y-intercept, and b is the slope of the resulting straight line fit.

The $RMSE_S$ estimates the model's linear (or systematic) error; hence, the better the regression between predictions and observations, the smaller the systematic error.

Unsystematic Root Mean Square Error ($RMSE_U$) was calculated as the square root of the mean squared difference in prediction-regressed prediction pairings within a given analysis region and for a given period.

$$\mathbf{RMSE_U} = \left[\frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I}(P_j^i - \widehat{P}_j^i)^2\right]^{0.5}$$ Equation 8.6

The unsystematic difference is a measure of how much of the discrepancy between estimates and observations is due to random processes or influences outside the legitimate range of the model.

The index of agreement (d–index) proposed by Willmott et al. (1985) was estimated using Equation 8.7. The d-index condenses all the differences between model estimates and observations within a given analysis region and for a given period (hourly and daily) into one statistical quantity. It is the ratio of the total RMSE to the sum of two differences – between each prediction and the observed mean, and each observation and the observed mean. Viewed from another perspective, the index of agreement is a measure of the match between the departure of each prediction from the observed mean and the departure of each observation from the observed mean. Thus, the correspondence between predicted and observed values across the domain at a given time may be quantified in a single metric and displayed as a time series. The index of agreement has a theoretical range of 0 to 1. According to the d-index, the closer the index value is to one, the better the agreement between the two variables that are being compared and vice versa.

$$d = 1 - \left[\frac{\sum_{i=0}^{n}(P_i - O_i)^2}{\sum_{i=0}^{n}(|P_i| - |O_i|)^2}\right]$$ Equation 8.7

where: n is the number of observations, P_i the predicted observation, O_i is a measured observation, $|P_i| = P_i - M$ and $|O_i| = O_i - M$ (M is the mean of the observed variable). The simulated model results were compared statistically to observe experimental measurements using Microsoft Excel.

8.3 Results and Discussion

8.3.1 Calibration

Since AquaCrop simulates crop growth and yield response to water availability, it is important to establish a good goodness of fit between model simulated and field observed soil water content. AquaCrop simulated soil water content ($R2 \geq 0.901$; RMSE $\leq$ 13.32%; $d \geq 1.000$) very well (Fig. 8.1), which gave confidence that other water-based crop processes were simulated based on good water availability prediction.

AquaCrop is a canopy level model (Mabhaudhi, Modi and Beletse, 2014). As such, the canopy, through its expansion, ageing, conductance and senescence, is central to the model as it determines the amount of water transpired, which in turn determines the amount of biomass produced (Raes et al., 2009b). AquaCrop simulated canopy cover ($R2 \geq 0.659$; RMSE $\leq$ 14.35%; $d \geq 0.999$), biomass ($R2 \geq 0.79$; RMSE $\leq$ 10.14%; $d \geq 0.908$), harvest index ($R2 \geq 0.967$; RMSE $\leq$ 3.55%; $d \geq 0.998$) and yield ($R2 \geq 0.923$; RMSE $\leq$ 3.82%; $d \geq 0.770$) satisfactorily for all three genotypes during calibration (Fig. 8.2). Root mean-square error was low, with high goodness of fit ($n = 16$), and Willmot's d–index values were close to 1 implying that model-predicted values were close to observed values. This gave confidence in calibration of the model and allowed model testing using independent data.

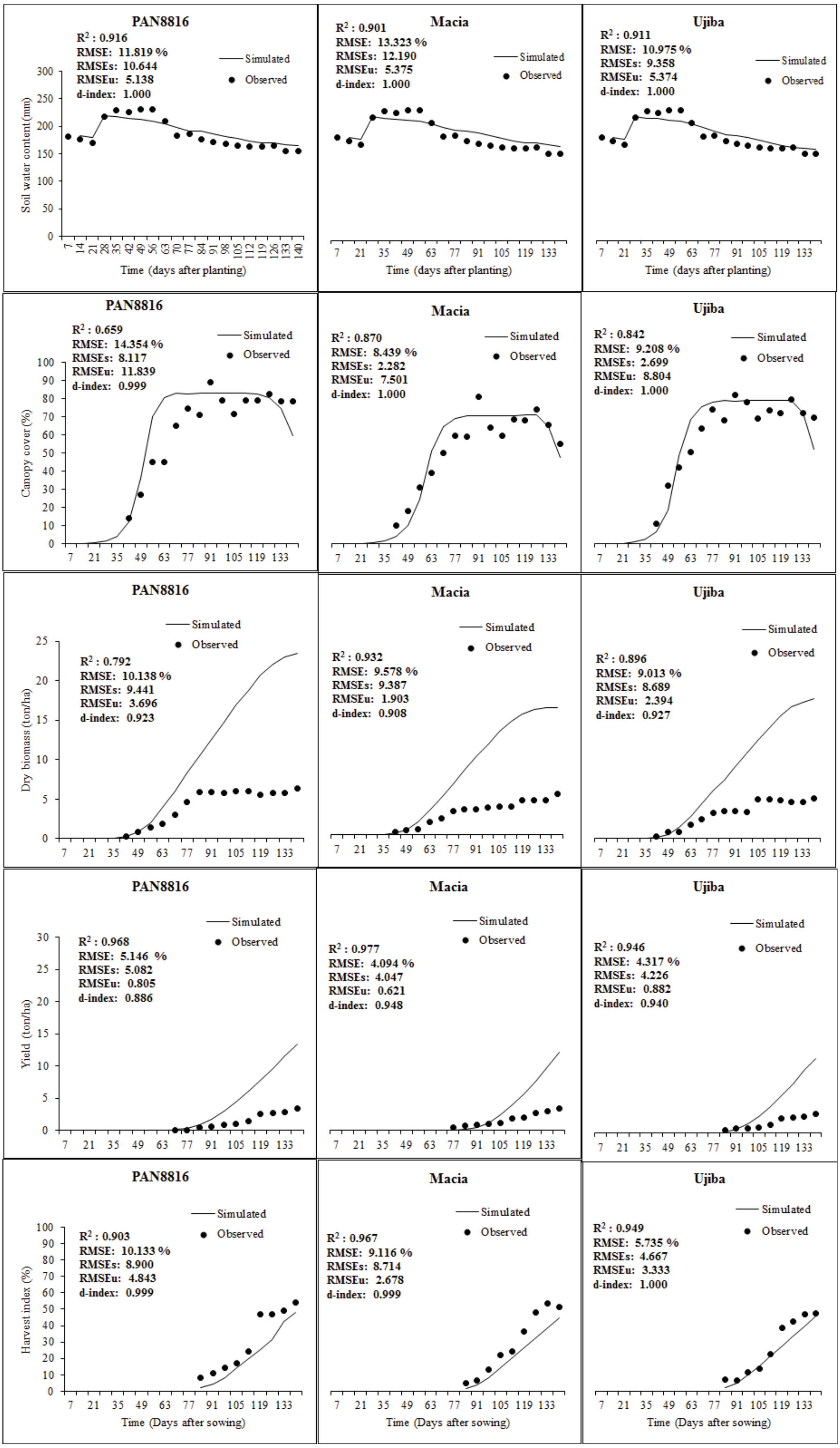

Figure 8.1: Simulated vs. observed canopy cover, biomass, yield, and harvest index for PAN8816, Macia and Ujiba sorghum genotypes for the calibration model run using 2013/14 Ukulinga growing season data.

8.3.2 Testing

There was good agreement between observed and simulated soil water content ($R2 \geq 0.710$; RMSE $\leq 22.73\%$; $d \geq 0.998$) and crop canopy cover ($R2 \geq 0.710$; RMSE $\leq 22.73\%$; $d \geq 0.998$) for all genotypes and planting dates. This showed that the model was capable of simulating water availability and canopy development under different environments (Fig. 8.3). This implies that the separation of soil evaporation from crop transpiration was captured well by the model. The result confirmed model robustness and consistency across environments. Once canopy senescence was triggered, the model simulated rapid canopy decline whereas in reality sorghum's canopy decline was moderate. This is because sorghum genotypes evaluated in the study employed osmotic adjustment and quiescence strategies which allowed for moderate canopy decline. The limitations of the model in capturing this aspect of sorghum resulted in a low goodness of fit between model simulated and observed values, especially under water stress.

With respect to the planting dates, the model simulated canopy cover well for early planting ($R2 \geq 0.843$; RMSE $\leq 13.91\%$; $d \geq 0.999$) and late planting ($R2 \geq 0.873$; RMSE $\leq 12.07\%$; $d \geq 0.999$) (Fig. 8.3). Model performance was satisfactory ($R2 \geq 0.710$; RMSE $\leq 22.73\%$; $d \geq 0.998$) for the optimal planting. Model performance for the optimal planting date was affected by observed low emergence at optimal planting due to low soil water availability during and shortly after sowing. This resulted in observed low canopy cover compared to model-simulated canopy cover (Fig. 8.3). In this instance, the model could be used to assess gaps between actual and potential canopy cover under field conditions. In field trials, time to physiological maturity was observed when a dark spot appeared on the opposite side of the kernel from the embryo, signalling completion of dry matter accumulation (Eastin et al., 1973). However, physiological maturity in model simulations was observed when dry matter accumulation ceased.

Under field conditions, physiological maturity occurred when canopy cover was relatively high, while for model simulations it coincided with relatively low or zero canopy cover. This resulted in a slight overestimation ($\leq 7.8\%$) of time to physiological maturity in the model (Table 8.3). Since AquaCrop uses canopy cover to estimate transpiration and calculate biomass accumulation, this potentially led to a carryover error in simulated biomass and yield. This would account for the overestimation of the two parameters. Adjusting canopy sensitivity to water stress (canopy expansion, stomatal closure, early senescence and harvest index) could potentially improve model simulation, especially during canopy senescence where model simulations were less than satisfactory. However, the relatively satisfactory performance of the model with minimum data input calibration confirms model simplicity and robustness and its suitability for use in areas with limited datasets.

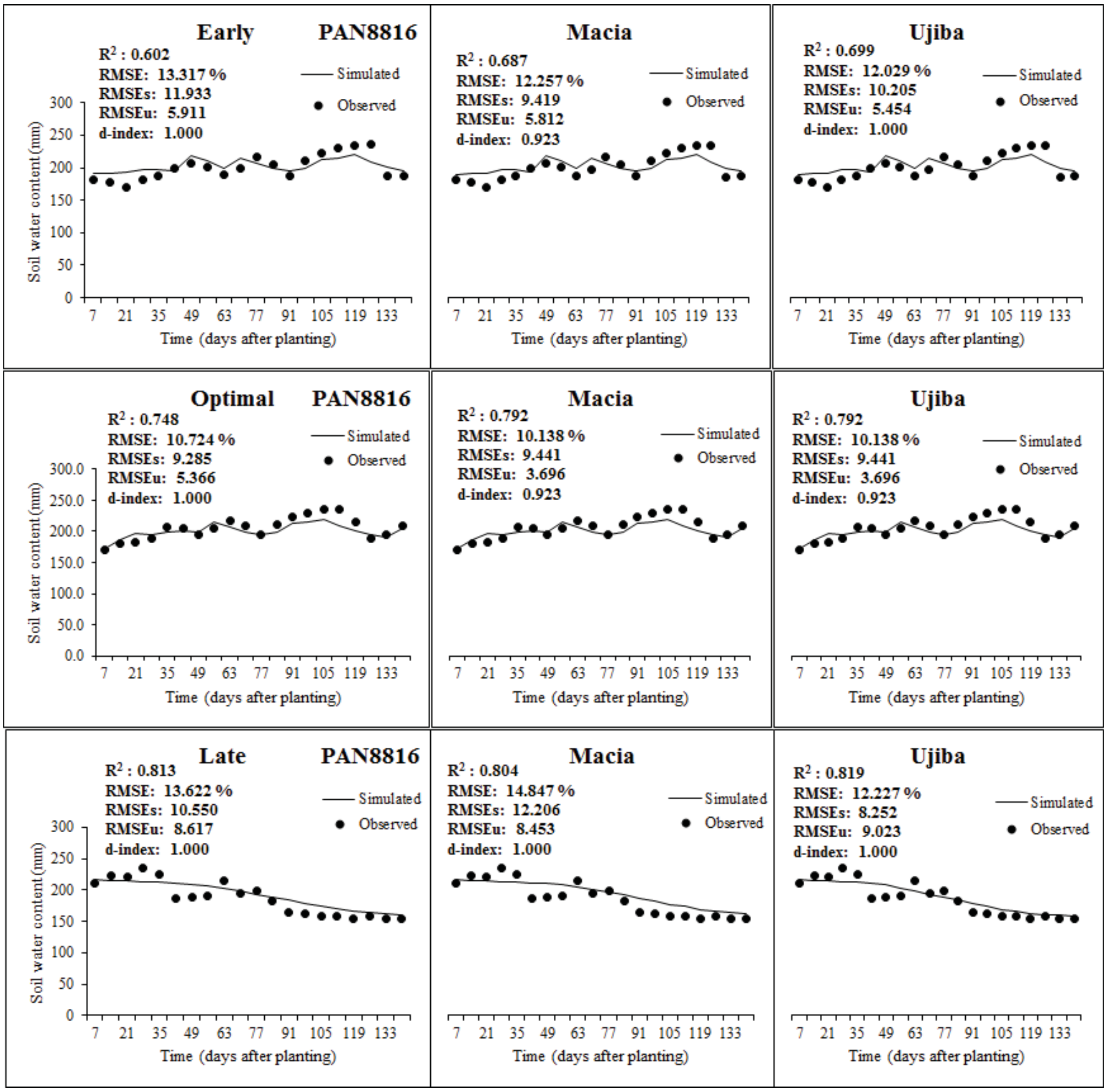

Figure 8.2: AquaCrop simulated and field observed soil water content for PAN8816, Macia and Ujiba sorghum genotypes planted at three different planting dates (early, optimal and late) within the 2014/15 growing season at Ukulinga.

AquaCrop separates the yield into biomass and harvest index (Raes et al., 2009b), where harvest index is the ratio of economic yield over total aboveground biomass. Biomass accumulation is calculated as a product of WP and transpiration. Thereafter, biomass partitioning into yield is a function of harvest index. Prediction of biomass ($R2 \geq 0.900$; $RMSE \leq 10.45\%$; $d \geq 0.850$) and yield ($R2 \geq 0.945$; $RMSE \leq 3.53\%$; $d \geq 0.783$) was very good (Figs 8.4 and 8.5). However, the model significantly over-estimated both biomass and yield, to generally be twice the observed values. On average, total biomass simulated by the model was 24.04, 20.68 and 20.70 t·ha-1, whereas observed biomass was 10.82, 10.36 and 6.09 t·ha-1, for early, optimal and late planting dates, respectively. Total yield simulated by AquaCrop was 12.24, 9.8 and 10.79 t·ha-1, whereas observed yield was 5.25, 5.31 and 3.16 t·ha-1, for early, optimal and late planting dates, respectively (Table 8.3). Expected sorghum yields are 3–8 t·ha-1 for genotypes used in the study. This implies that observed biomass and yield were within expected yields, whilst confirming that the model simulations over-estimated these variables. Good canopy simulation by the model resulted in confidence in transpiration predictions used in biomass calculation. Model simulations exhibited differential water stress levels across planting dates, with highest water stress levels during the late planting date for all genotypes. This implies that water stress played a major role in biomass and yield determination. Determining the genotype specific water stress coefficients (Ks) could potentially improve model yield simulations. A default sorghum WP parameter (33.3 g·m-2) was used in simulations. Water productivity for C4 cereal crops is generally accepted to be 30–35 g·m-2 (Raes et al., 2010). However, this conservative parameter may need to be determined for local genotypes, as it is a potential source of error in model overestimation of yield.

Table 8.3: AquaCrop simulated (Sim.) and experimentally observed (Obs.) time to physiological maturity in three sorghum genotypes planted at different planting dates. MOM stands for model overestimation margin.

Planting date	Genotype	Time to physiological maturity			Biomass			Yield		
		Obs. (days)	**Sim. (days)**	**MOM (%)**	**Obs. (ton/ha)**	**Sim. (ton/ha)**	**MOM (%)**	**Obs. (ton/ha)**	**Sim. (ton/ha)**	**MOM (%)**
Early	PAN8816	133	140	5.3	10.95	25.14	129.6	5.31	11.28	112.42
	Macia	140	140	0	11.70	23.47	100.6	6.38	9.93	55.64
	Ujiba	140	140	0	9.80	23.50	139.8	4.07	10.47	157.25
Mean		**138**	**140**	**1.8**	**10.82**	**24.04**	**122.2**	**5.25**	**10.56**	**101.14**
Default sorghum file					**10.82**	**19.54**	**80.6**	**5.25**	**6.68**	**27.2**
Optimal	PAN8816	126	133	5.6	9.87	21.54	118.2	4.99	9.97	99.80
	Macia	140	134	–4.3	11.28	20.19	79.0	6.79	9.30	36.97
	Ujiba	126	135	7.1	9.93	20.30	104.4	4.16	9.78	135.1
Mean		**131**	**134**	**6.35**	**10.36**	**20.68**	**99.6**	**5.31**	**9.68**	**82.30**
Default sorghum file					**10.36**	**18.67**	**80.2**	**5.31**	**6.53**	**23.0**
Late	PAN8816	126	135	7.1	5.00	20.44	308.8	2.71	10.50	287.45
	Macia	133	140	5.3	6.33	20.27	220.2	3.26	9.83	201.53
	Ujiba	126	140	11.1	6.93	21.38	208.51	3.50	10.14	189.71
Mean		**128**	**138**	**7.8**	**6.09**	**20.70**	**240.0**	**3.16**	**10.16**	**221.52**
Default sorghum file					**6.09**	**18.67**	**206.6**	**3.16**	**6.61**	**109.2**

In the interest of comparison with previous work, simulations obtained from experimental sorghum genotypes were compared to those obtained from simulations using the AquaCrop default sorghum file. In comparison, simulations using the default file instead of three study genotypes exhibited excellent predictions of yield (R2 ≥ 0.816; RMSE ≤ 1.90%; d ≥ 0.900) with relatively high overestimation error (23.0–109.2%). Yield overestimation error was low (23.0% and 27.2%) for early and optimal planting dates, respectively, where rainfall was relatively high and well distributed across planting season. For the late planting date, when relatively low, highly irregularly distributed rainfall was observed, yield overestimation was high (109.2%). Canopy cover was poorly simulated (R2 ≥ 0.11; RMSE ≤ 41.03%; d ≥ 0.995) suggesting that canopy characteristics of local genotypes differ significantly from those of the AquaCrop default crop file. This highlights the need to perform additional experiments to determine canopy sensitivity to water stress for calibration of the three genotypes used. Since AquaCrop is a canopy-level, yield response to water model, it is of primary importance to accurately predict canopy cover to predict biomass and yield. Therefore, improved yield and biomass estimations by the default file are pointless without a corresponding improvement in canopy cover predictions.

Despite the limitations in calculating biomass, the model could capture the build-up of harvest index (Fig. 8.6) very well ($R2 \geq 0.902$; $RMSE \leq 7.17\%$; $d \geq 0.987$). This implies that the contribution of harvest index as a source of error in over-estimation of yield was minimal. Model over-estimation of biomass and yield increased for late-planted sorghum genotypes, where water stress was observed to be relatively high in comparison to other planting dates under experimental field trials and simulations. This suggests that canopy sensitivity to water stress should also be accurately described when calibrating the model for local sorghum genotypes. Developing genotype specific Ks values for the sorghum genotypes used in this study could improve model simulations of biomass and yield. Overall, canopy cover, biomass, harvest index and yield model simulations were very good for all genotypes and planting date environments.

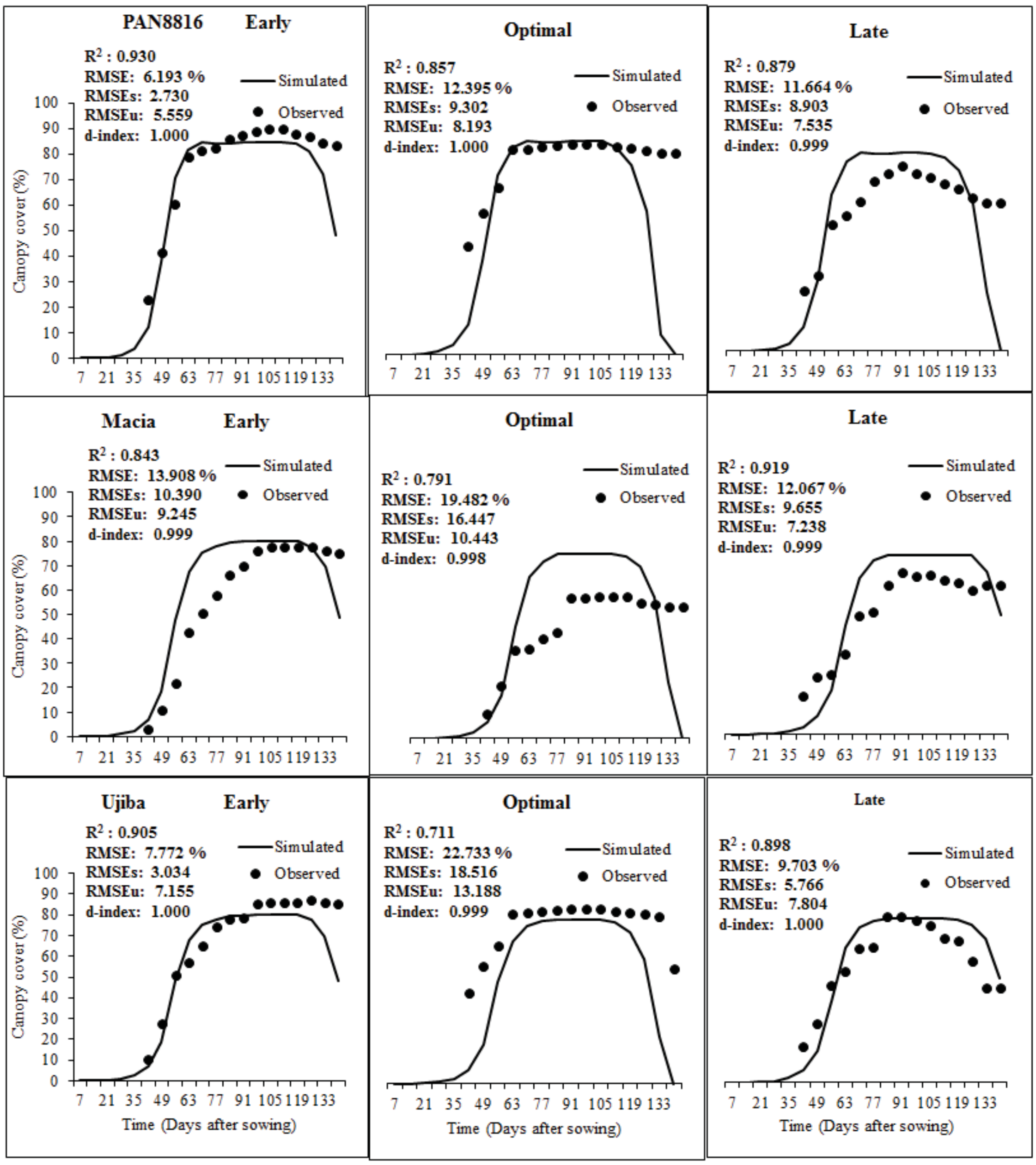

Figure 8.3: AquaCrop simulated and field observed canopy cover for PAN8816, Macia and Ujiba sorghum genotypes planted at three different planting dates (early, optimal and late) within the 2014/15 growing season at Ukulinga.

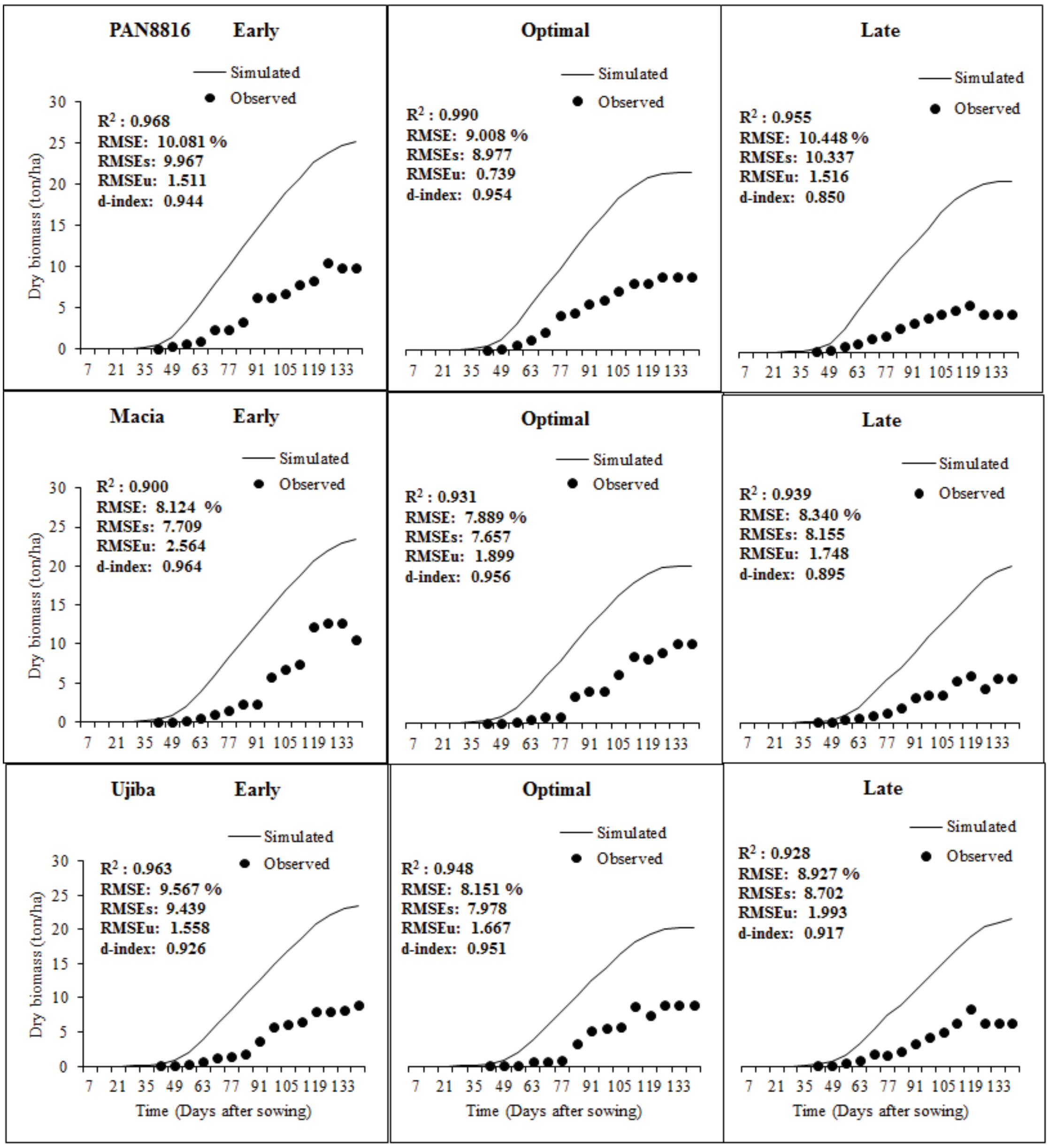

Figure 8.4: AquaCrop simulated and field observed aboveground dry biomass for PAN8816, Macia and Ujiba sorghum genotypes planted at three different planting dates (early, optimal and late) within the 2014/15 growing season at Ukulinga.

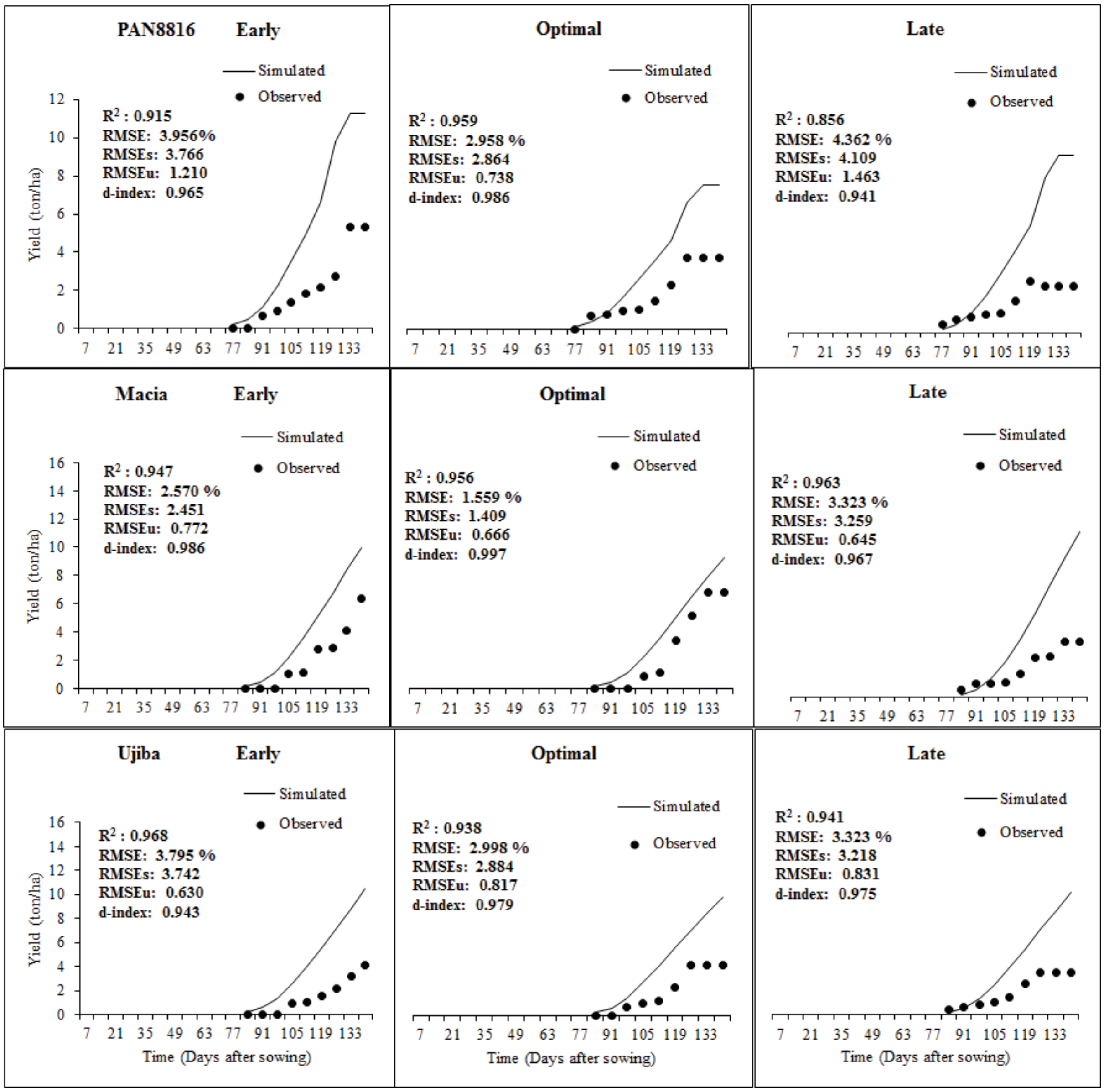

Figure 8.5: AquaCrop simulated and field observed panicle yield for PAN8816, Macia and Ujiba sorghum genotypes planted at three different planting dates (early, optimal and late) within the 2014/15 growing season at Ukulinga.

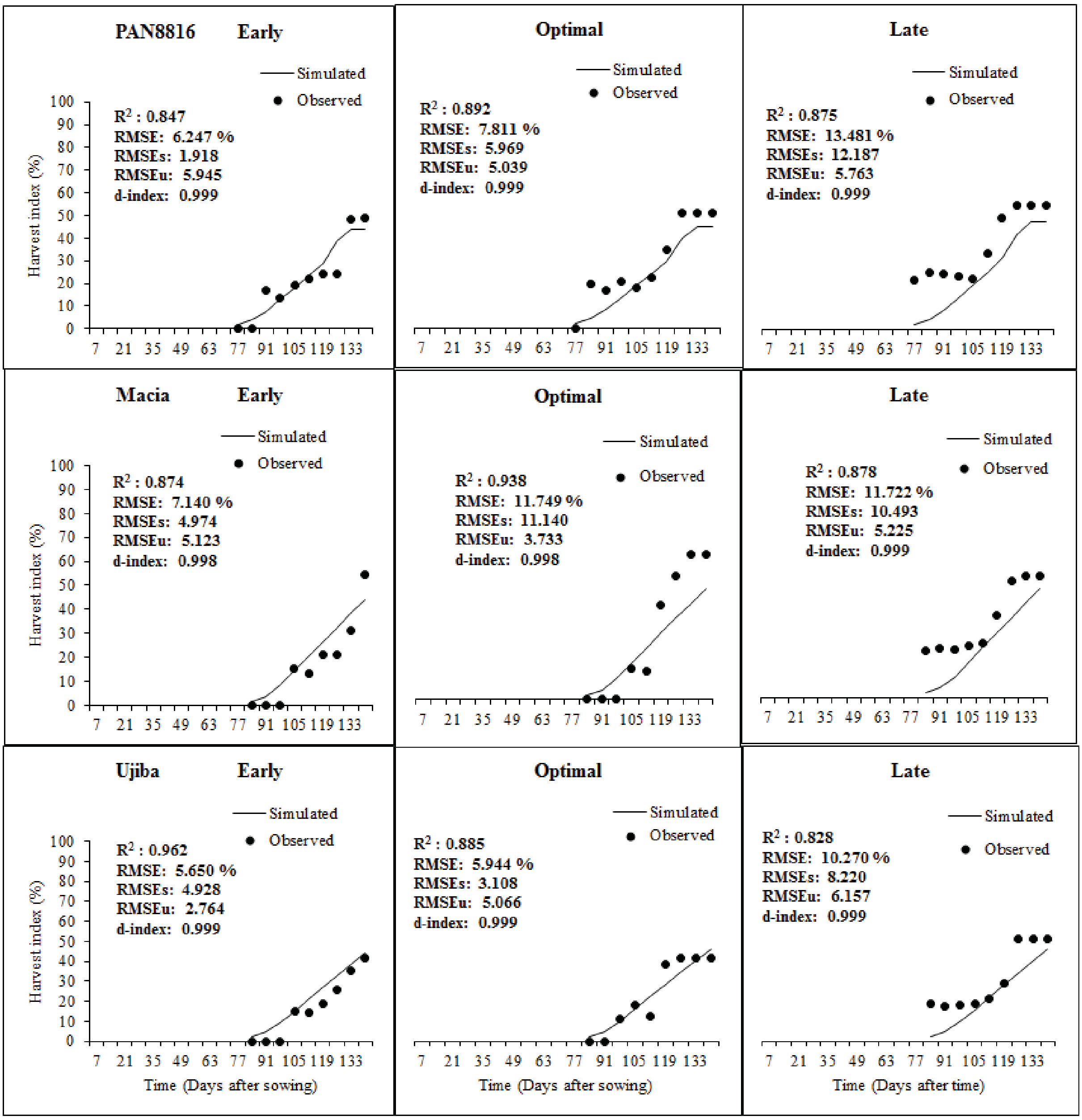

Figure 8.6: AquaCrop simulated and field observed harvest index for PAN8816, Macia and Ujiba sorghum genotypes planted at three different planting dates (early, optimal and late) within the 2014/15 growing season at Ukulinga.

8.4 Conclusion

The model could simulate canopy cover, biomass accumulation, harvest index and yield relatively well for all sorghum genotypes and planting dates. The model did not accurately capture sorghum canopy decline as it did not consider sorghum's quiescence growth habit which allows for delayed canopy senescence under water-limited conditions. Conservative parameters in the default sorghum crop may not necessarily represent those of local genotypes, and this potentially contributes to overestimation of biomass and yield in the model. Despite model calibration simulating canopy cover relatively well, overestimation of biomass and yield suggests that conservative parameters, such as water productivity (WP), canopy sensitivity to water stress and water stress coefficient, additionally require calibration for local genotypes to improve calibration. Where water conservation and crop growth characteristics are of primary importance, the use of minimum data input calibrated files is recommended due to very good simulations of crop canopy and phenological development. In cases where biomass and yield simulation is important, the use of the default file is recommended to reduce overestimation error. The results of this study suggest that where local sorghum genotypes differ significantly in growth and development characteristics from the default file, the use of minimal data input calibration potentially compromises prediction of crop yield. In terms of model application where extensive data is absent, it is recommended that users add the parameters (WP, canopy sensitivity to water stress, and water stress coefficient) that are suggested in this study to improve calibration. For new sorghum cultivars that differ significantly in growth and development characteristics from the default crop file, it may be necessary to do a full calibration where possible to achieve good overall predictions of crop response to water availability.

References

Allen, R., Pereira, L., Raes, D., Smith, M., 1998. Crop evapotranspiration (Guidelines for computing crop water requirements). FAO Irrigation and Drainage Paper, No. 56. Rome. 297 Pp.

Charyulu, C.D., Bantilan, M.C.S., Reddy, B.V., Kumar, A.A., Ahmed, I., Davis, J., 2014. Estimation of ICRISAT Sorghum Research Spillover benefits – Strategies for Research Prioritization and Resource Allocation. Patancheru.

Department of Agriculture and Forestry (DAFF) 2010. Sorghum production guidelines. Pretoria, South Africa.

Eastin, J.D., Hultquist, J.H., Sullivan, C.Y., 1973. Physiological maturity in grain sorghum. Crop Sci. 13, 175–178.

Farahani, H.J., Izzi, G., Oweis, T.Y., 2009. Parameterization and evaluation of the AquaCrop model for full and deficit irrigated cotton. Agron. J. 101, 469–476.

Food and Agriculture Organization (FAO), 2008. The state of food and agriculture. Biofuels: prospects, risks and opportunities. Rome, Italy.

Food and Agriculture Organization (FAO), 2012. Reference Manual, Annex I – AquaCrop, Version 4.0. Rome, Italy.

Fjelde, H., Von Uexkull, N., 2012. Climate triggers: Rainfall anomalies, vulnerability, and communal conflict in Sub-Saharan Africa. Pol. Geo. 31, 444–453.

Geerts, S., Raes, D., Gracia, M., Miranda, R., Cusicanqui, J.A., Taboada, C., Mendoza, J., Huanca, R., Mamani, A., Condori, O., Mamani, J., Morales, B., Osco, V., Steduto, P., 2009. Simulating yield response of Quinoa to water availability with AquaCrop. Agron. J. 101, 499–508.

Hoogenboom, G., Jones, J.W., Traore, P.C.S., Boote, K.J., 2012. Experiments and data for model evaluation and application. In: Kihara, J., Fatondji, D., Jones, J.W., Hoogenboom, G., Tabo, R., Bationo, A., (Eds). Improving Soil Fertility Recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT). Springer, Dordrecht, Netherlands. pp 9–18.

Hsiao, T.C., Heng, L.K., Steduto, P., Rojas-Lara, B., Raes, D., Fereres, E., 2009. AquaCrop — the FAO crop model to simulate yield response to water III parameterization and testing for maize. Agron. J. 101, 448–459.

Hsiao, T.C., Fereres, E., Steduto, P., Raes, D., 2012. AquaCrop parameterization, calibration, and validation guide, in: Steduto, P., Hsiao, T.C., Fereres, E., Raes, D., (Eds). Crop yield response to water. FAO Irrigation and Drainage Paper 66. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. pp 70–87.

Jamieson, P.D., Porter, J.R., Wilson, D.R., 1991. A test of computer simulation model ARC-WHEAT1 on wheat crops grown in New Zealand. Field Crops Res. 27, 337–350.

Loague, K., Green, R.E., 1991. Statistical and graphical methods for evaluating solute transport models; overview and application. J. Contam. Hydrol. 7, 51–73.

Karunaratne, A.S., Azam–Ali, S.N., Al–Sharref, I., Sesay, A., Jorgensen, S.T., Crout, N.M., 2011. Modeling canopy development of bambara groundnut. Agric. Forest Meteorol. 150, 1007–1015.

Mabhaudhi, T., 2012. Drought tolerance and water–use of selected South African landraces of taro (*Colocasia esculenta* L. Schott) and bambara groundnut (*Vigna subterranea* L. Verdc). PhD thesis. University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Mabhaudhi, T., Modi, A.T., Beletse, Y.G., 2014. Parameterisation and testing of AquaCrop for a South African bambara groundnut landrace. Agron. J. 106, 243–251.

Moeletsi, M.E., Walker, S., 2012. Rainy season characteristics of the Free State Province of South Africa with reference to rain-fed maize production. Water SA 38(5), 775–782.

Raes, D., Sithole, A., Makaru, A., Millford, J., 2004. Evaluation of first planting dates recommended by criteria currently used in Zimbabwe. Agric. Forest Meteorol. 125, 177–185.

Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2009a. AquaCrop—The FAO crop model to simulate yield response to water: II. Main algorithms and soft ware description. Agron. J. 101, 438–447.

Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2009b. AquaCrop–The FAO crop model to simulate yield response to water: Reference Manual Annexes., www.fao.org/nr/water/aquacrop.html.

Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2010. Reference manual, Chapter 3 – Calculation procedures. AquaCrop version 3.1. FAO, Land and Water Division. Rome, Italy.

Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2012. Reference manual, Chapter 2 – AquaCrop version 4.0. FAO, Land and Water Division. Rome, Italy.

Steduto, P., Hsiao, T.C., Fereres, E., 2007. On the conservative behaviour of biomass water productivity. Irri. Sci. 25, 189–207.

Steduto P, Hsiao, T.C., Raes, D., Fereres, E., 2009. AquaCrop—The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agron. J. 101, 426 –437.

Singh, P., Wani, S.P., Pathak, P., Sahrawat, K.L., Singh, A.K., 2011. Increasing crop productivity and effective use of water in rainfed agriculture, in: Integrated watershed management in rainfed agriculture. CRC Press (Taylor and Francis), London, UK. pp 315–347.

Smith, B., 2006. The farming handbook. University of KwaZulu Natal Press. South Africa. pp 220–226.

Swemmer, A.M., Knapp, A.K., Snyman, H.A., 2007. Intra-seasonal precipitation patterns and above-ground productivity in three perennial grasslands. J. Ecol. 95, 780–788.

Takele, A., Farrant, J., 2013. Water relations, gas exchange characteristics and water use efficiency in maize and sorghum after exposure to and recovery from pre and post-flowering dehydration. Afr. J. Agric. Res. 8, 6468–6478.

Water Research Commission (WRC). 2014. WRC Knowledge Review 2013/14. Project No. K5/2274//4. Determining water use of indigenous grain and legume food crops. Pretoria, South Africa.

Willmott, C.J., Akleson, G.S., Davis, R.E., Feddema, J.J., Klink, K.M., Legates, D.R., Odonnell, J., Rowe, C.M., 1985. Statistic for the evaluation and comparison of models. J. Geophys. Res. 90, 8995–9005.

CHAPTER 9

SIMULATING YIELD AND WATER USE OF A SORGHUM–COWPEA INTERCROP USING APSIM

Chimonyo, V.G.P., Modi, A.T. and Mabhaudhi, T.

9.1 Introduction

In rural sub-Saharan Africa (SSA), rainfed agriculture is the most important sector for providing food security (Gowing and Palmer, 2008). However, the region is characterized by low yields owing to low and variable rainfall, degraded soils and inherently infertile soils (Chikowo et al., 2010, 2014). In addition, rural farmers lack access to capital, technical knowhow and inputs (Nkonya et al., 2015). Low levels of investment in infrastructure in the region also make farming challenging, especially for resource-poor farmers. In addition, climate change predictions indicate an increase in the occurrence and severity of weather extremes such as drought and flooding within the region (Connolly-Boutin and Smit, 2015). Intercropping has emerged as a suitable approach for sustainable intensification of agriculture, especially under water limited conditions. However, due to past research emphasis on monocrop systems, information that can assist in formulation of policy for promotion of intercropping in rainfed cropping systems is scant. Therefore, there is need to generate relevant information that can be used to enhance promotion of intercropping within rainfed cropping systems.

Intercropping is defined as the growing of two or more crops (species or varieties) within the same spatial and temporal resolution (Willey, 1979). Under limited water availability, intercropping has been observed to improve productivity per unit area through increased water use efficiency (Rezig et al., 2010; Tsubo et al., 2003; Yang et al., 2011). Conversely, the advantages of intercropping across SSA can easily be confounded by heterogeneous agro-ecological characteristics within existing rainfed cropping systems (Cooper et al., 2008). To come up with suitable recommendations across diverse agro-ecologies, multi-location studies are often necessary. However, time, cost and technical skill required to study spatial and temporal production of intercropping systems using field experiments make multi-location trials less desirable to implement (Lobell et al., 2009). To address these limitations, crop simulation models (CSM) such as Agricultural Production Systems Simulator APSIM (Carberry et al., 1996) have since been employed (Boote et al., 1996) as tools for generating useful data for assessing current and future productivity.

Agricultural Production Systems Simulator APSIM (Carberry et al., 1996) was primarily developed to address short and long-term consequences of crop management, quantify crop response to management and environment interactions, and to provide synergistic representation of various disciplines involved within farming systems (Wang et al., 2002). It has been used extensively to evaluate crop production under a wide range of management systems and environmental conditions (Grenz et al., 2006; Carberry et al., 2009; Dimes et al., 2011; Nape, 2011; Mohanty et al., 2012; Luo et al., 2014). Evidence in literature shows that it has capacity to simulate productivity and resource use in intercrop systems (Robertson et al., 2004; Dimes et al., 2011; Harris et al., 2008; Knörzer and Lawes, 2011). Despite the evidence that APSIM can simulate intercrop systems, its practical use in managing intercrop systems is very limited. This is mainly attributed to insufficient literature that supports the use of APSIM as a decision support tool for resource use of intercrop systems.

To date, the APSIM model has been used to simulate an array of cropping systems across a wide range of environments as it can simulate the response of a range of crops to different climates and soils under alternative management options (Carberry et al., 1999). Its capability to simulate crop responses to climatic and management variations has been derived from rigorous testing. Therefore, the capability of APSIM to simulate intercrop systems also requires such rigour to improve its performance as a tool used in generating relevant and accurate data, especially under water scarcity. In this study, it was hypothesized that APSIM can be used to simulate performance of a sorghum–cowpea intercrop grown under rainfed conditions. Therefore, the aim of the study was to evaluate the performance of a locally adapted APSIM sorghum-cowpea model for simulating growth, productivity and water use of a sorghum-cowpea intercrop system.

9.2 Materials and Methods

9.2.1 Site and plant material description

Field experiments were conducted at the University of KwaZulu–Natal's Ukulinga Research Farm (29°37'S; 30°16'E; 775 m a.s.l.) in Pietermaritzburg, South Africa, over two summer seasons (2013/14 and 2014/15). Ukulinga Research Farm receives a mean annual rainfall of 790 mm received mostly between the months of October and April. The summer months are warm to hot with an average temperature of 26.5°C. At Ukulinga, the dominant soils are chromic luvisols (FAO soil classification). Based on profile pit description, soil texture is clay to clay–loam with an effective rooting depth of 0.6 m (Table 9.1). Soil physical properties have been shown to affect movement and availability of soil water for plants. Results of soil chemical properties showed that the carbon (%) for the top 0.2 m layer was 2.3% while N was 0.3%. From these the initial C:N ratio was calculated as 7.67.

The APSIM intercrop model will be adapted for a sorghum hybrid (PAN8816) and a cowpea (Brown mix) variety. PAN8816 is a medium to late maturing hybrid variety with average yield of yield ranging between 2 – 5 t ha^{-1} under optimum conditions. For cowpea, brown mix variety (Capstone Seeds) was used for the study based on previous reports that suggested that it had fairly good drought tolerance (Modi and Mabhaudhi, 2013). The brown mix variety has a spreading growth habit, making it ideal for intercropping. For full description of experimental site, refer to Chimonyo et al. (2016).

9.2.2 Experimental design and management

The field experiment was set up as a split–plot design with sub-plots laid out in randomised complete blocks within the main plots, and replicated three times. The main plot was water regime with three levels [full irrigation (FI), deficit irrigation (DI) and rainfed (RF)]. Sub–plots comprised intercrop combinations; sole sorghum, sole cowpea and sorghum–cowpea intercrop system. For full detail on treatments and plot layout, refer to Chimonyo et al. (2016). Based on results of soil fertility analyses, an organic fertiliser, Gromor Accelerator® (30 g N kg^{-1}, 15 g P kg^{-1} and 15 g K kg^{-1}) was applied to supply 52 kg N ha^{-1}. Fertiliser application was designed to meet the nutritional requirements for sorghum, the main crop, and applied six weeks after emergence. Routine weeding was done using hand hoes. Insect pests and animal attacks were scouted for at each visit to the field.

Table 9.1: Soil water properties at different depths for soil at the experimental site at UKZN–Ukulinga Research farm.

Depth (m)	TX[8]	BD[1] (g cm^{-3})	Airdry[2]	LL15[3]	DUL[4] (mm depth^{-1})	TAW[5]	SAT[6]	KS[7]	SOC[9] %	KLs[10]	KLc[11]
0 – 0.10	Clay	1.29	0.34	21.04	33.54	12.5	48.66	20.9	2.3	1.0	1.0
0.10 – 0.30	Clay	1.47	0.69	47.61	69.94	24.63	97.89	18.18	1.2	0.8	0.6
0.30 – 0.60	Clay	1.4	2.39	79.23	110.42	34.13	149.83	13.92	0.8	0.6	0.4
Average*/Total		1.39*	3.42	147.88	213.9	71.26	296.38	17.67*	-	-	-

[1] Bulk density; [2] Airdry -Hydroscopic water content; [3]. LL15 -Permanent wilting point; [4] DUL -Field capacity; [5] Total available water; [6] SAT – Saturation; [7] KS - Hydraulic conductivity; [8] TX – Soil texture; [9] SOC – Soil organic content; [10] KL-root penetration parameter for sorghum and [11] KL-root penetration parameter for cowpea.

9.2.3 Model description

The Agriculture Production systems SIMulator (APSIM) is a point scale model and simulates production outputs of the management of a single homogenous field over a specified period (McCown et al., 1996). The model comprises components/modules that can be sub-divided into biological (crop, pasture, surface residue), environmental (water balance and movement of solutes in the soil, soil organic matter and N, residue, phosphorus, erosion) and management (tillage, grazing, intercropping, irrigation, fertilization). The APSIM model can simulate resource use in intercrop systems and according to Keating et al. (2003); the absence of any direct communication among the crop modules allows this to happen. The canopy module within APSIM is the main reason why resource competition between two crop species can be simulated. When a simulation is conducted involving solar radiation and water competition between crop species, the canopy module or the arbitrator is plugged in and determines resources intercepted by each component of the intercrop using leaf area index (LAI) extinction coefficient and height for each crop. Arbitration for water and nitrogen uptake is done based on APSIM changing the order each day (on a rotational basis) in which the competing species are given the opportunity to capture soil resources. A maximum of ten crops can be specified for intercropping.

9.2.4 Simulation

Simulating water use and productivity of sorghum–cowpea intercrop system was done using APSIM version 7.7. To simulate the intercrop system, weather (MET), crop (modified sorghum and cowpea), soilWAT and canopy modules were linked to the APSIM model engine. Modules also included were management, surface residue, irrigation and fertilizer. To improve the accuracy of model simulation, local adaptation of the model modules was done first using weather, soil and crop parameters measured *in situ* during 2013/14 growing season. Where necessary and to improve model performance, fine tuning of parameters was done by adjusting observed input parameters within the range of a calculated standard deviation (±SD) of observed data. Thereafter, the model was tested against observed data obtained from field experiments established during 2014/15 growing season. The model was calibrated in the first season and then evaluated in the second season.

APSIM – MET: To create the MET file, daily weather data were obtained from an automatic weather station (AWS) located less than 1 km from the experimental field and within Ukulinga Research Farm. The AWS is part of the Agricultural Research Council – Institute for Soil, Climate and Water (ARC–ISCW) network of automatic weather stations. Daily weather for the

MET file were maximum (Tmax) and minimum (Tmin) air temperature (°C), solar radiation (Rad, MJ m^{-2}), rainfall (mm) and Priestley Taylor reference evapotranspiration – (PT ET_o, mm). Obtained weather data from the period between 1st October 2013 and 31st May 2015 was converted to .xml format. Thereafter, values of average ambient temperature (TAV) and the annual amplitude in monthly temperature (AMP) were calculated and input into the .MET files via "tav_amp". It should be noted that there were several incidences of hailstorms during the 2013/14 and 2014/15 growing season.

APSIM soil: The soil module within APSIM contains generic soil profiles for Africa (Koo and Dimes, 2013). Each soil file is described by soil texture, fertility and rooting depth. To determine a suitable generic soil file for the simulation, soil physical properties (soil texture and SOC) as well as effective rooting depth were determined *in situ* using a soil profile pit. The soil was described as clayey (49% clay) with high soil fertility (SOC = 2.3%) and shallow rooting depth (60 cm). Based on this soil profile description, the soil file within the generic African soil profile that best fit this description was selected as Clay_Shallow_HF_101mm.

The SoilWAT model was used to describe movement of water and solutes within the soil system. The SoilWAT module is a cascading water balance model that simulates daily runoff, drainage, ET_O, soil evaporation saturated and unsaturated flow of water and associated influxes and out fluxes of solutes. To improve the model's accuracy for simulating soil water dynamics within the intercrop system, values of soil water properties derived using the hydraulic properties calculator (http://hydrolab.arsusda.gov/soilwater/Index.htm) were used to describe soil water properties within SoilWAT for each horizon (Table 9.1).

The soil/root water extraction coefficient (KL, d – 1) and root penetration parameter (XF, 0 – 1 multiplier on the rate of root growth) for sorghum and cowpea were set to default values found in APSIM crop descriptor files for each crop, as there were no observed values. The soil evaporation coefficient, U (6 mm) was calculated from long-term average of PT-ET_o while the CONA (3 mm $d^{-0.5}$) was estimated from soil texture (Littleboy et al., 1999). CONA (mm/day0.5) is defined as the second stage sol evaporation. This commences after the first drying stage (U), once the limiting availability of water exerts a controlling influence on soil evaporation and is time-dependent. Values of CONA and U were input in to the model to improve simulation of water lost through bare soil evaporation. The rate at which water drains from the profile, that is the soil water conductivity (SWCON, d–1) 0.23, was obtained from Kiniry et al. (1989). For unsaturated water flow, we used the default values for APSIM coefficients (diffus_const and diffuse_slope). Based on observed soil texture and colour, soil albedo (0.13) was obtained from Jones and Kiniry (1986)

***APSIM-Crop modules*:** During preliminary runs of the intercrop model, it was observed that existing cultivars for sorghum and cowpea over-estimated biomass and yield. Crop coefficients for sorghum (medium maturity cultivar) and cowpea (spreading cultivar) crop files were modified using parameters derived from sole plots of sorghum and cowpea grown under optimum (stress free) conditions (Table 9.2). Crop specific coefficients modified for sorghum included minimum and maximum leaf number, leaf appearance rate, thermal time to phenological events and radiation use efficiency (RUE). For cowpea, only RUE was modified (Table 9.2).

For sorghum, a leaf was defined as one that is fully expanded, fully exposed, and had a collar. A fully expanded and exposed trifoliate was considered as a leaf for cowpea. Leaf number for sorghum and cowpea were counted on a weekly basis from emergence up to physiological maturity. Within each respective crop file in APSIM, minimum and maximum leaf numbers for sorghum and cowpea were higher than what was observed under field conditions. Minimum and maximum leaf numbers were adjusted downward to improve model simulations (Table 9.2). Leaf appearance rate (°Cd $leaf^{-1}$) in sorghum was the intervening period between sequential emergences of leaves on the main stem of a plant and is also rendered as phyllochron. Regressing number of leaves that were visible on thermal time (base 8°C) from emergence calculated leaf appearance rate. Thermal time required to develop the most leaf ligule – Rate 1 (leaf appearance rate between emergence and floral initiation), thermal time required for the appearance of the last leaf ligule – Rate 2 (leaf appearance rate between floral initiation and appearance of flag leaf ligule) and leaf number below flag leaf above which leaf appearance rate changes from rate 1 to rate 2 were changed within APSIM sorghum file according to observed data (Table 9.2). Solar radiation is the basis for biomass production within APSIM and this is achieved through a crop specific coefficient that describes the relationship between biomass and intercepted photosynthetically active radiation – radiation use efficiency (RUE) (g MJ^{-1}) (Sinclair and Horie, 1989). Observed RUE values for sorghum (1.25 g MJ^{-1}) and cowpea (1.65 g MJ^{-1}) were input into the APSIM sorghum and cowpea files. During model iterations, it was observed that biomass production was over-estimated. To improve model simulation of biomass, RUE of cowpea and sorghum were adjusted within the range of calculated SD (±0.45 and 0.23, respectively). Radiation use efficiency of 1.15 and 1.19 g MJ^{-1} were used as input values for RUE of sorghum and cowpea, respectively (Table 9.2).

APSIM – *Irrigation:* The module “irrigate on date” was used to apply irrigation on dates corresponding to actual irrigation dates. Observed irrigation applied per event for the field experiment was calculated to be on average 12 mm ± 5.5 mm (SD) twice or three times a week depending on rainfall received and calculated crop water requirement for sorghum for the that week. Based on this, irrigation amount within the irrigation module was set to 12 mm per event with an irrigation efficiency of 90%. Weekly rainfall (R) data was obtained from the AWS. Measurements of initial values of volumetric SWC for model adaption were not available. Therefore, the simulation period was set to start on the 1st of December 2013 and 1st of October 2014 to allow the model to calculate a soil water balance and initial volumetric SWC at planting. For the 2013/14 planting season, the experiment was established under rainfed conditions. Initial soil water within the SoilWAT module was obtained by running a fallow simulation with two-year historic data prior to and up to 15 days after 2013/14 crop establishment. Volumetric SWC at planting was modelled to be 31% and this value was used to describe initial SWC in the model. During 2014/15 planting season, before planting irrigation was applied to recharge the soil back to field capacity (DUL= 36.5% volumetric SWC). Within the initial soil water module of SoilWAT module, initial soil water was set at DUL and "filled from the top".

APSIM – Management: Within the management module, sowing using variable date for intercropping module was used to represent management options within the simulation. Within the module, sowing date was set to fall in between 13 – 20 January 2014 for model adaptation and 13 – 20 November 2015 for model testing. For both runs, sorghum and cowpea were sown when at least 20 mm of rainfall had been received within a 10-day period, and water content in the topsoil (5 – 20 cm depth) was at least 50%. The planting criteria set for simulation was not always in line with actual conditions observed during planting of field experiments. Sowing depth was set at 0.05 m for both sorghum and cowpea. Sowing density for sorghum and cowpea were set to reflect densities in the experiment, which were 2.6 and 1.3 plants m^{-2}. Similarly, row spacing was set at 0.75 m to reflect actual crop management practise. An application of 52 kg ha^{-1} N fertilizer 60 days after planting was used for sorghum while no fertilizer was added in cowpea sowing module.

9.2.5 Model evaluation

Data on biomass accumulation, final yield, and cumulative WU and WUE for intercropped sorghum and cowpea were collected from the field experiments for evaluating model performance. Data collected during the 2014/15 growing season was used to test the performance of the model. Due to monkey attacks yield for cowpea was not available for model testing.

For the field experiments, crop water use (WU) for sorghum-cowpea intercrop system was calculated as the residual of a soil water balance:

$$WU = P + I - D - R - \Delta SWC \quad \text{Equation 9.1}$$

where: WU = evapotranspiration (mm), P = precipitation/rainfall (mm), I = irrigation (mm), D = drainage (mm), R = runoff (mm), and ΔSWC = changes in soil water content (mm).

Runoff (R) was assumed to be zero since erosion was negligible in the plots as it had a slope of less than 3% (Seelig and Alfonso, 2007). Drainage was also considered as negligible since the observed impeding layer at 0.6 m restricted downward movement of water beyond the root zone. Within the model, WU was determined as the sum of crop water uptake from the whole profile (sorghum Ep + cowpea Ep) and soil evaporation (Es).

Changes in soil water content (SWC) were measured using a PR2/6 profile probe connected to an HH2 handheld moisture meter (Delta–T, UK). Soil water content was measured at depths corresponding to observed soil layers (Table 9.1) (0.10, 0.30 and 0.60 m). After each irrigation event, amount of water added (I) was determined from rain gauges randomly placed across the experimental plots.

At harvest, water use efficiency was calculated for yield (were possible) and biomass for the whole system (sorghum + cowpea). Observed WUE was calculated using measured values of the systems' water use (WU), and biomass and yield values for sorghum and cowpea. APSIM does not calculate WUE directly; however, it is able to simulate inputs (WU, yield and biomass) used in its calculation. Water use efficiency was calculated as follows:

$$WUEy = \frac{Y}{WU} (kg\ mm^{-1}) \quad \text{Equation 9.2}$$

$$WUEb = \frac{B}{WU} (kg\ mm^{-1}) \quad \text{Equation 9.3}$$

where: WUEy and WUEb = water use efficiency (kg mm^{-1} ha^{-1}) calculated based on yield (Y) and biomass (B), respectively, Y = total economic yield (sorghum + cowpea) (kg ha^{-1}), B = total biomass (sorghum + cowpea) (kg ha^{-1}) and WU = the crop water use (WU) (mm).

To evaluate model performance, simulated outputs (S) were statistically analysed against observed (O) data. Simulated and observed time to phenological stages, leaf number, biomass, yield, WU and WUE were compared using Correlation of determination (R^2) and total root mean squared error (RMSE) and systematic and unsystematic components of the root mean squared error (RMSEs and RMSEu,). Values of R^2 range between 0 and 1 with high values indicating less error variance. Since the interpretation of R^2 is *n* dependent, low values are only acceptable if *n* is huge. Then again, R^2 values are sensitive to outliers and insensitive to additive and proportional differences between S and O. Therefore, using normalized statistical parameters such as RSME can improve reliability of R^2 and d-index results. For interpretation of results, RMSEu should approach RMSE for a model's performance to be considered as good.

Table 9.2: Modification of sorghum crop coefficients based on observed results from 2013/14 growing season.

Crop	Parameter description	Coefficient name	Value
Sorghum	Base temperature	Tbase	8**
	Leaf number at emergence	leaf_no_at_emerg	1*
	Minimum leaf number	leaf_no_min	8
	Maximum leaf number	leaf_no_max	14
	Thermal time required to develop the most leaf ligule	leaf_app_rate1 (oCd)	55
	Thermal time required to develop last leaf ligule	leaf_app_rate2 (oCd)	42
	Leaf number below flag leaf above which leaf appearance rate changes from rate 1 to rate 2	leaf_no_rate_change	2.5
	Radiation use efficiency (g (biomass) MJ^{-1})	RUE	1.15
	Thermal time between emergence and end of juvenile stage	tt_emerg_to_endjuv	120
	Thermal time between end of juvenile stage to floral initiation	tt_endjuv_to_init	140
	Thermal time between appearance of flag leaf to flowering	tt_flag_to_flower	179
	Thermal time between flowering to start of grain filling	tt_flower_to_start_grain	85
	Thermal time between flowering to physiological maturity	tt_flower_to_maturity	865
Cowpea	Radiation use efficiency (g (biomass) MJ^{-1}) (Cowpea)	RUE	1.19

9.3 Results and Discussion

9.3.1 Local adaptation

9.3.1.1 Phenology

The dataset used to determine genetic coefficients for sorghum and cowpea gave good agreement between simulated and observed values for phenology. Model simulations for phenology in sorghum were satisfactory (RMSE = 4.4 °Cd). The RMSEu (4.1 °Cd) was shown to approach RMSE, although there was a 7.7% difference (Fig 9.1). The RMSEs (1.7 °Cd) approached zero, therefore model performance was deemed as good. Model simulations for cowpea phenology were also satisfactory (RMSE = 7.4 °Cd) (Fig 9.1). The RMSEu (6.9 °Cd) was shown to approach RMSE, although there was a 7.0% difference. The RMSEs (2.7 °Cd) approached zero, therefore, model performance was deemed good.

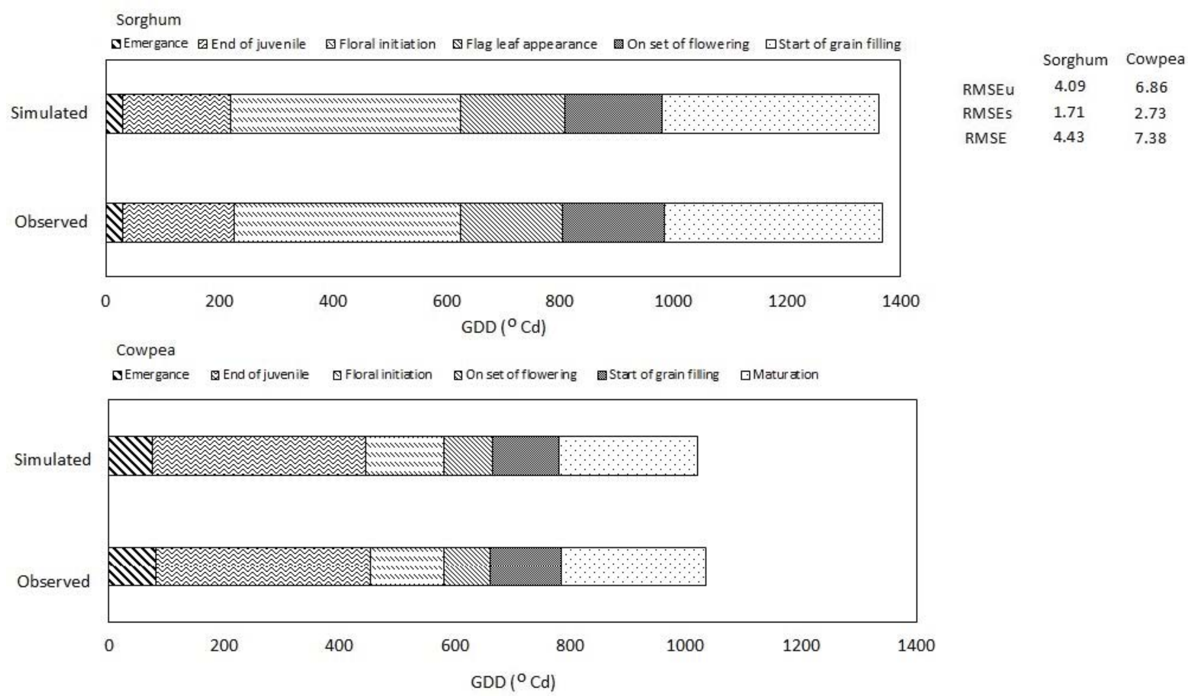

Figure 9.1: Local adaptation of APSIM model for sorghum and cowpea showing observed and simulated values for phenology and statistical output for its evaluation.

Plant phenology is a critical component for adaptation, especially if resources are limited and are being competed for. After the adjustments of crop specific coefficients, the model's ability to accurately simulate phenology for both cowpea and sorghum within the intercrop system was improved. APSIM crop files has its own default cultivars for different maturity classes. In cases were new cultivars are being modelled, local adaptation should always be considered to improve model simulation. Overall, the model could simulate phenological development of both sorghum and cowpea when both crops are grown in an intercrop system.

9.3.1.2 Leaf number

Model simulation for leaf number for sorghum was satisfactory (R^2 = 1.0 and RMSE = 5.8) although the model over estimated by one leaf. The RMSEu (5.8) was shown to approach RMSE while the RMSEs (0.88) approached zero. Model simulations for leaf number for cowpea were also satisfactory (R^2 = 1.0 and RMSE = 4.0) (Fig 9.2) although the model over-estimated by an average of three leaves. The RMSEu (3.4) was shown to approach RMSE with a 12% difference and the RMSEs (1.9) was somewhat large but approaching zero.

While the R^2 outputs showed that there was generally a good model fit, this could be misleading due to the small population used in the analysis. Based on the RMSE and its components, model simulation of intercropped sorghum and cowpea leaf number was satisfactory. Adjustments of leaf development rates (rate 1 and 2) (Table 9.1) for sorghum ensured that the model could capture leaf development for the cultivar simulated. The good fit between observed and simulated leaf number indicates that the default crop coefficients for cowpea leaf development within the model adequately described cowpea cultivar used. In addition, the model could simulate the response of cowpea as the understory in the intercrop system. Therefore, APSIM can capture eco-morphological adaption within an intercrop system appropriately. On the other hand, the low observed leaf number for both sorghum and cowpea could be that during data collection the cotyledon leaves were not included; however, these are considered as leaves by the model.

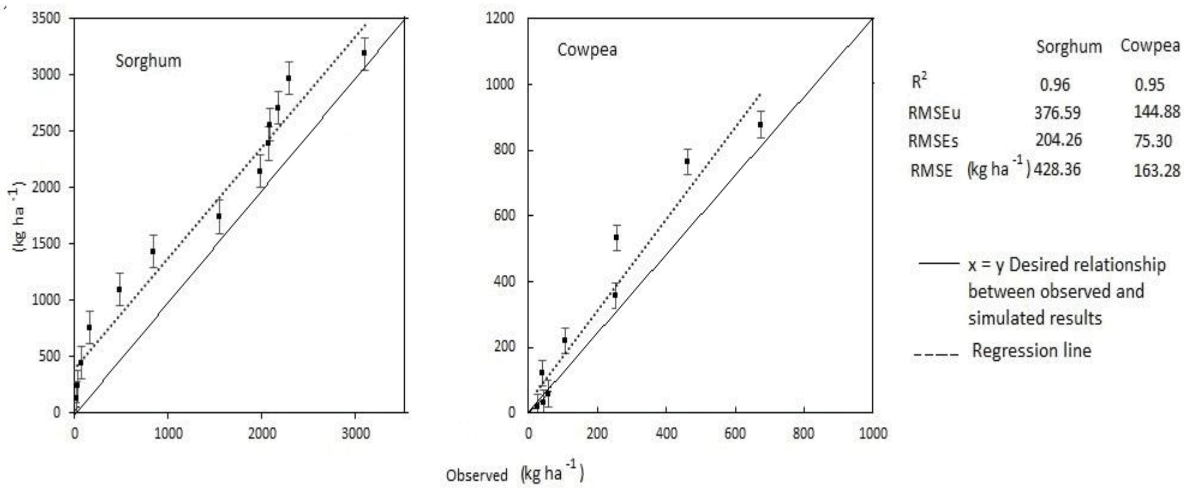

Figure 9.2: Local adaptation of APSIM model for sorghum and cowpea showing observed and simulated values for leaf number and statistical output for its evaluation. Vertical bars on observed data represent standard error (±).

9.3.1.3 Leaf area index

There was poor agreement between simulated and observed results of LAI for both sorghum and cowpea. For sorghum and cowpea, R^2 was low (0.5 and 0.2, respectively) while RMSE (0.1 and 0.2, respectively) was observed to be high (Fig 9.3). With regards to LAI, the model's performance with respect to simulation of LAI was deemed poor (Fig 9.3). Results of RMSEs show large systematic and unsystematic error within the data set. The large error could be attributed to the loss in LA by both sorghum and cowpea because of hail damage. It could be that the simulated LAI depicts the actual canopy size for the crop components of the intercrop system had it not been damaged by hail during early growth stages. On the other hand, the APSIM model has been observed to perform poorly for prediction of LAI. For instance, Asseng et al. (1998) observed R^2 = 0.6 for wheat while Hammer et al. (2010) observed an R^2 = 0.9 for sorghum with a sample size of less than 10. The interpretation of R^2 is highly dependent on the number of observations (*n*). When *n* is low (e.g. $n < 10$), high values ($R^2 > 0.9$) would be acceptable and vice versa.

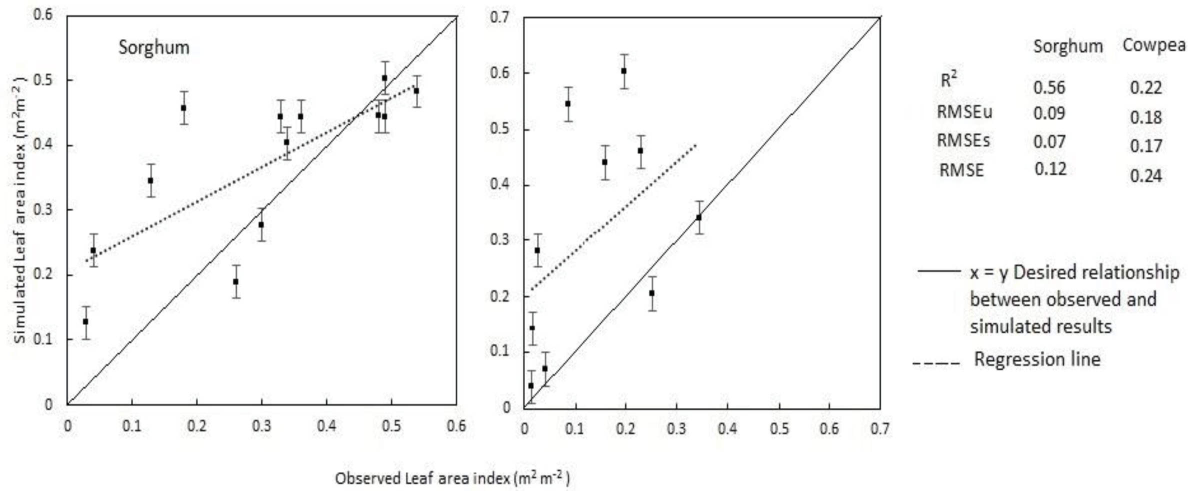

Figure 9.3: Local adaptation of APSIM model for sorghum and cowpea showing observed and simulated values for leaf area index (m^2 m^{-2}) and statistical output for its evaluation. Vertical bars on observed data represent standard error (±).

9.3.1.4 Biomass, yield, WU and WUE

The model simulation for the intercrop biomass was deemed satisfactory based on statistical output. Overall, R^2 was high (0.96 and 0.95) while RMSE (428.4 and 204.3 kg ha^{-1}) was observed to be low for both sorghum and cowpea, respectively. In addition, RMSEu for both sorghum and cowpea were observed to approach RMSE (Fig 9.4). The satisfactory model performance could be attributed to the fact that biomass is calculated as a derivative of RUE. The model's ability to partition radiation down the canopy of sorghum - cowpea intercrop proved to be a useful strategy used in simulating biomass accumulation within the intercrop. This, coupled with the use of calculated RUE values for both cowpea and sorghum, increased the accuracy of predicted biomass. Given that the model was input with data from the sole crops of sorghum and cowpea, there was a reasonable fit between observed and simulated data for sorghum and cowpea grown within the intercrop system. This gave sufficient evidence that the model is eco-physiologically appropriate for simulating intercrop systems. Therefore, APSIMs ability to allocate resources within heterogeneous crop stands make it an applicable tool in assessing resource use in intercrop systems.

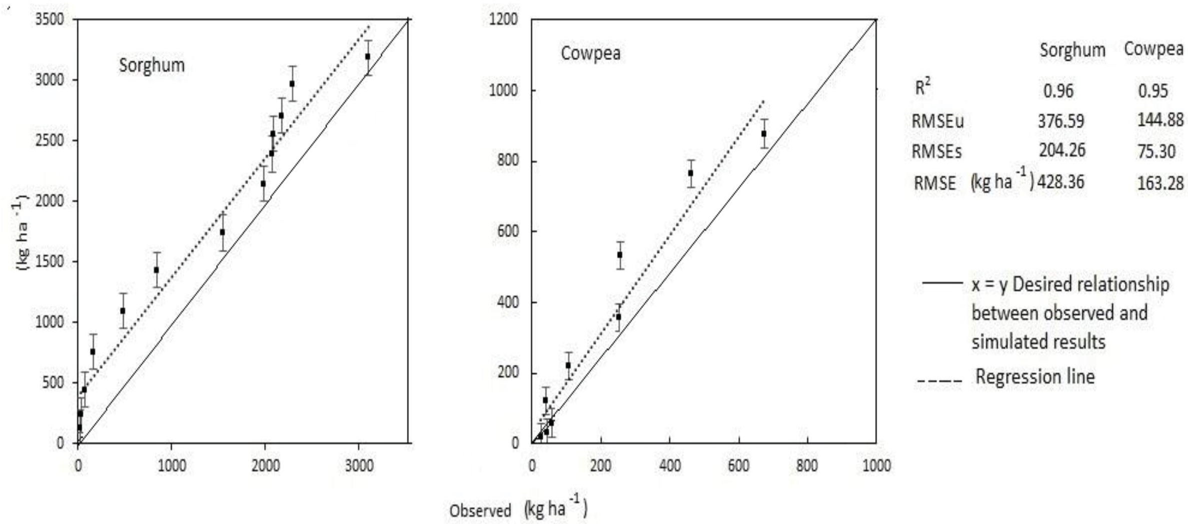

Figure 9.4: Local adaptation of APSIM model for sorghum and cowpea showing observed and simulated values for biomass (kg ha^{-1}) and statistical output for its evaluation. Vertical bars on observed data represent standard error (±).

Table 9.3: Local adaptation of APSIM model for sorghum and cowpea showing observed and simulated values for Crop water use (mm), yield (kg ha^{-1}) and water use efficiency, and statistical output for its evaluation.

		Simulated	**Observed**	**RMSE**	**% Difference**
Crop water use (mm)		329.9	307.4	22.5	7.0
Yield (kg ha^{-1})	Sorghum	1156.6	1239.4	82.7	7.0
	Cowpea	145.0	189.8	44.8	31.0
WUE_y[1] (kg mm^{-1} ha^{-1})		4.3	4.2	0.3	2.0
WUE_b[2] (kg mm^{-1} ha^{-1})		16.4	14.3	2.1	15.0

[1]WUEy – Grain water use efficiency for combined sorghum and cowpea yield; [2]WUEb – Biomass water use efficiency for combined sorghum and cowpea biomass.

Model simulation for sorghum yield was satisfactory as indicated by low RMSE (82.7 kg ha^{-1}) with a difference of 7% from observed yield (Table 9.3). This was consistent with results of simulated phenology and biomass. On the other hand, model simulation for cowpea yield was poor (RMSE = 44.8 kg ha^{-1}) with an overestimation of 31% (Table 9.3). Within the sorghum crop module, final grain weight is proportional to 15 and 20 % of leaf and stem final weight. For cowpea, grain weight is derived from harvest index (0.28). The over-estimation of cowpea yield by the model could be attributed to the carry over error brought about by the slight overestimation of biomass such that more biomass was produced and subsequently partitioned to yield via HI. The model's response of yield to biomass was similar to those observed by Cheeroo-Nayamuth et al. (2000) and Moeller et al. (2014) who observed over-prediction of yield due to over-prediction of biomass. The model could explain more than 75% of observed yield in the intercrop under field conditions (Table 9.3). This would suggest that, other than intercropping and its possible effect on resource availability, cowpea succumbed to other yield reducing factor(s) that are not adequately accounted for by the model. With regards to this, the model can be used for assessing yield gaps.

Good simulations of crop water use (ET) by the model were also observed (RMSE = 33.3 mm); however, there was an over-estimation by 7% (Table 9.3). Similar to biomass simulation, over-estimation of ET could also be attributed to over-estimations of LAI (Table 9.3). In addition, the role of cowpea as a live mulch could have reduced estimations of (soil evaporation) Es relative to (crop water uptake) Ep fraction. These results are similar to those observed by Balwinder-Singh et al. (2011) who observed an over-estimation of ET when the effect of mulching on crop water use was simulated in APSIM. The observed results suggest that APSIM was unable to fully capture the role played by cowpea to reduce soil surface evaporation within the intercrop system.

The WUE calculated based on model simulated yields (WUEy) and biomass (WUEb) of both sorghum and cowpea showed very good fit (0.34 and 2.11 kg mm^{-1} ha^{-1}, respectively) for simulated and observed results (Table 9.3). The WUEy difference (2.1%) between the observed and simulated for yield was within a reasonable margin (Table 9.3). The large differences (14.8%) observed for WUEb can be attributed to over-estimation of both sorghum and cowpea biomass yield relative to crop water use. Simulations of ET and WUE can still be considered acceptable since they are in line with observed values.

9.3.2 Model testing

9.3.2.1 Phenology

Similar to observed results from field experiments where water regime did not affect time to phenological event for sorghum and cowpea (Chimonyo et al., 2016), model simulated phenological events were not affected by differences in water availability. Conversely, model simulations for sorghum and cowpea phenology under different water regimes were very good (RMSE = 2.5 and 5.2 °Cd, respectively) (Fig 9.5). The observed RMSE for the different water regimes was consistent with results of local adaptation indicating model stability and robustness for sorghum–cowpea intercrop systems simulated under different water management scenarios.

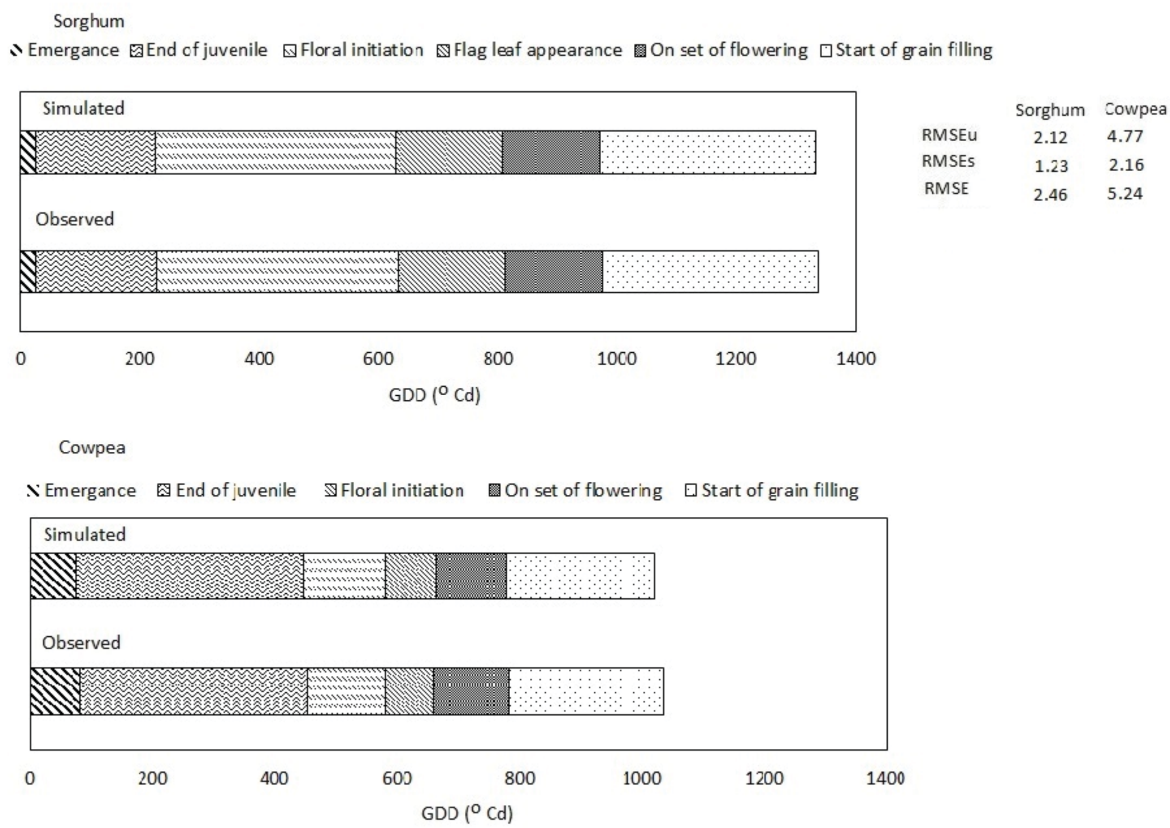

Figure 9.5: Comparison of observed and simulated values for sorghum and cowpea phenology and statistical output for its evaluation.

The ability to accurately simulate phenology is critical for crop production as it has huge implications for crop management practices and crop cultivar selection. The importance of phenology also stems from its direct influence on canopy development (Baker and Reddy, 2001), biomass production and partitioning (Reynolds et al., 2008) and yield production (Tao et al., 2006). Phenological stability of sorghum and cowpea within an intercrop system can ensure that the crop development cycle is maintained even under limiting conditions and is considered as an important drought tolerance trait (Fuad-Hassan et al., 2008). The model was therefore able to mimic low sensitivity of intercrop responses to varying water management strategies.

9.3.2.2 Leaf number

Model simulations for leaf number for sorghum under different water regimes were generally poor ($R^2 \geq 0.6$ and RMSE = 2.8). Contrary to this, model simulation for cowpea leaf number under the different water regimes was satisfactory as the overall RMSE (9.5) was low, RMSEu (8.5) was approaching RMSE and RMSEs (3.32) was observed to be approaching zero.

Although the model did not give a good fit for sorghum and cowpea leaf number across the water regimes (Fig 9. 6), it could simulate the probable responses of leaf appearance for sorghum and cowpea when grown as an intercrop system across different water regimes. Within the model, sorghum leaf number is not sensitive to a reduction in water availability and this was consistent with field observations. Similar to model adaptation, differences in simulated and observed leaf number for sorghum for the three water regimes was because of how a leaf was defined during field observations. In this study, substantial defoliation of plants in the field experiment occurred due to hail damage at 79 DAP (718.8 °Cd) resulting in significant loss in leaves. In nature and as described in the model, number of leaf primordia in sorghum is genetic and equal to stem nodes; their development initiated at germination. On the other hand, in cowpea, genotype and environment interactions, and management practices such as intercropping, have been observed to affect primary and secondary branches and subsequently leaf formation. The model captured the effect of intercropping on cowpea leaf number adequately.

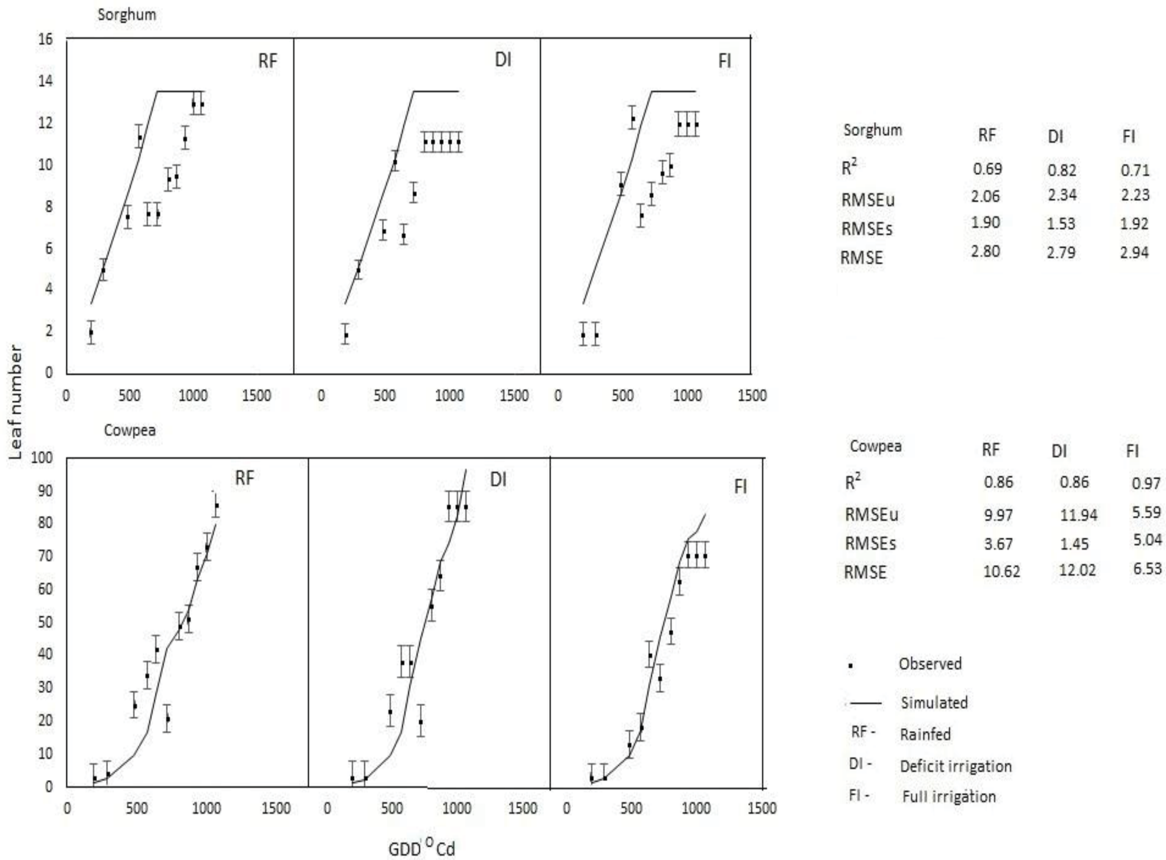

Figure 9.6: Comparison of observed and simulated values for sorghum and cowpea leaf number (kg ha^{-1}) under different water regimes and statistical output for its evaluation. Vertical bars on observed data represent standard error (±).

Although cowpea leaf number within the field experiment was also affected by hail, plants managed to regrow most of their leaves due to the presence of secondary branch nodes on primary branches. With the absence of the hailstorm, model output would suggest that there was an under-estimation of leaf number for cowpea. With the increase in occurrence of extreme weather events such as hailstorms, the weather subroutines that can be used to highlight observed extreme weather events that are not easily captured during model runs can improve model simulations and use as tools in risk management.

9.3.2.3 Leaf area index

Model simulations of LAI for the crop components of sorghum–cowpea intercrop under the different water regimes were generally poor (Fig 9.7) as shown by the statistical outputs of R^2, RMSE and its components. For both the crop components, the model over-estimated LAI by 36%

±6 and 15% ± 7 for sorghum and cowpea, respectively. During local adaptation of the model, tillering, which often occurs after floral initiation, was not observed in the field experiment and this agreed with simulated results. Under field conditions, tillering is a sensitive parameter, affected by soil water availability and photoperiod (Kim et al., 2010). Late planting for experiments established during the 2013/14 resulted in photoperiods of less than 12 hrs and this could have suppressed tillering. Early planting (photoperiod > 13 hrs) during the 2014/15 experiment resulted in tillering which in turn resulted in high observations of LAI. Canopy development is simulated on a whole plant basis through a relationship between total plant leaf area (TPLA) and thermal time. TPLA integrates the number of fully expanded leaves, their individual size, and tiller number, and includes an adjustment for the area of expanding leaves (Keating et al., 2003). This could have resulted in the model underestimating LAI.

Similarly, model performance for cowpea LAI did not always show a good fit across water regimes. Within the model, leaf area development per plant is simulated as a sigmoidal function of thermal time since emergence (Brown et al., 2014); however, development of observed LAI did not follow that pattern of development but was more of a power function type of graph. This resulted in the initial under-estimation of cowpea LAI. These results are consistent with reports by Garrido et al. (2013) and Brown et al. (2014) who also observed an initial under-estimation of wheat LAI in APSIM. This would suggest that, for improved model simulations, additional routines, which allow switching from sigmoid to other functions, should be incorporated into APSIM's plant modules.

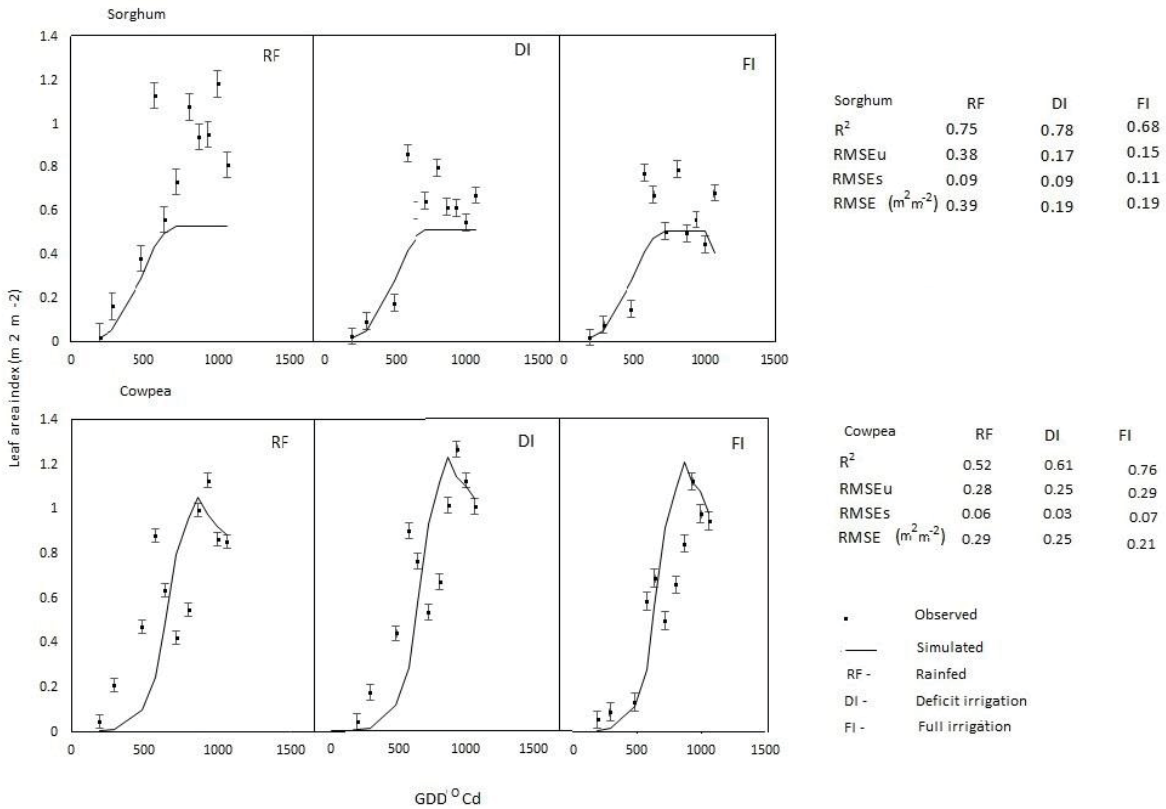

Figure 9.7: Comparison of observed and simulated values for sorghum and cowpea leaf area index (m^2 m^{-2}) under different water regimes and statistical output for its evaluation. Vertical bars on observed data represent standard error (±).

9.3.2.4 Biomass

Overall, the model simulation of biomass for the sorghum-cowpea intercrop at different water regimes was deemed satisfactory. Model performance for sorghum and cowpea biomass within the intercrop and across the different water regimes was good and this was attributed to its conservative behaviour with RUE. These results confirmed results of local adaptation. Therefore, concerning biomass simulation, the model was robust, especially if the coefficient RUE is accurately calculated. The model was able to capture differences in biomass production under different water regimes. Under RF conditions, the observed low biomass for sorghum and cowpea were attributed to increase in root to shoot ratio. Under limited water supply, sorghum and cowpea are known to increased root to shoot ratio to increase root volume for enhanced soil water extraction; a drought tolerance mechanism. Estimation of root to shoot ratio calculated from model simulation of root and above ground biomass showed that it increased with reduction in water availability (FI (0.20) < DI (0.22) < RF (0.28). This shows that the model could capture response of biomass partitioning between roots and above ground in relation to water availability and intercropping. Therefore, the model can be used to quantify the trade-offs of resource limitation such as reduced water availability in mixed cropping systems.

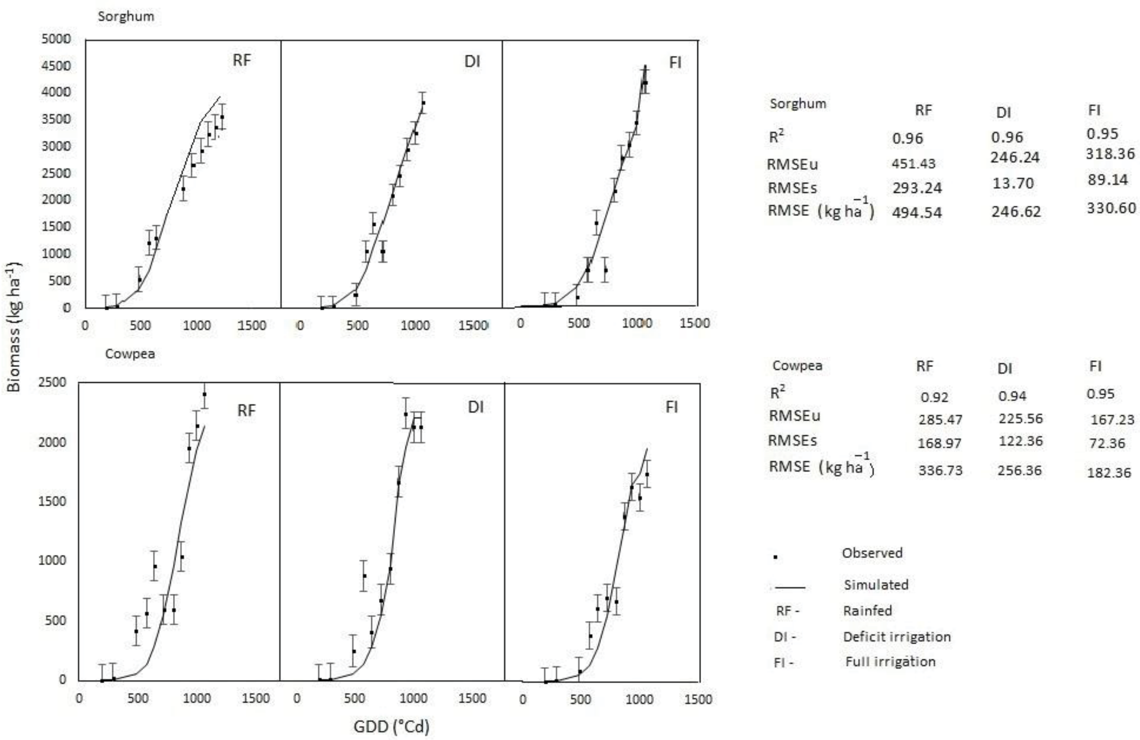

Figure 9.8: Comparison of observed and simulated values for sorghum and cowpea biomass (kg ha^{-1}) under different water regimes and statistical output for its evaluation. Vertical bars on observed data represent standard error (±).

9.3.2.5 Yield, water use and water use efficiency

Model simulations of sorghum yield under DI and RF were very good (RMSE = 37.9 and 36.0 kg ha^{-1}, respectively) while simulation under FI it was satisfactory (145.38 kg ha^{-1}). Under DI and FI conditions, simulated yield was respectively 3.5 and 3.3% higher while under RF conditions a larger difference of 14.9% was observed. The large difference between simulated and observed yield for sorghum under rainfed conditions could be attributed to over-estimation of biomass (6.5%) and subsequently yield. Under field conditions, low availability of water results in a reduction in canopy size to minimize loss of water through transpiration. Reduction in canopy size results in reduction in the amount of radiation intercepted resulting in a reduction in biomass RUE relative to well-watered conditions. The use of a RUE coefficient parameterized under optimum conditions may have resulted in a poor simulation of biomass under water-limited conditions, which in turn result in an overestimation of yield. In addition, the over-estimation of biomass and yield under RF conditions suggest that the APSIM model might not be sensitive to water. To improve simulations of biomass and yield, there is need to improve calibrations for soil–water and water stress indices to improve sensitivity of the model to low water availability.

Model simulations of crop water use (WU) by the intercrop system showed that it increased with increase in water availability (RF = 306.3 > DI = 361.5 > FI = 383.6 mm). Model simulations for WU for sorghum–cowpea intercrop system under FI and DI were very good (RMSE = 8.2 and 8.1 mm, respectively) while simulation under RF were satisfactory (RMSE = 24.11 mm) (Table 9.4). A close look at model output showed that increase in water availability did not influence crop water uptake (Ep) [FI = 113.3, DI = 113.0, RF = 111.5 mm (mean = 112.5 mm ± 1.0 SD)]. Based on this output, it suggests that transpiration was unaffected by reduction in water availability. In nature, low availability of water results in a reduction in transpiration due reduction in stomatal conductivity. In this case, the model appropriately captured sorghum physiology. One of the unique attributes of sorghum's drought tolerance is its ability to maintain high rates of stomatal conductance under water limiting conditions, which is achieved through enhanced water capture, and maintenance of internal tissue water status. On the other hand, increasing water availability increased soil evaporation (Es) [FI = 269.1, DI = 255.0, RF = 224.1 mm (mean = 249.4 mm ± 23 mm SD)]. Increased frequency of soil surface wetting resulted in more soil evaporation.

Results of WUEb calculated from simulated biomass and WU for the sorghum-cowpea intercrop system showed a good fit with WUEb calculated from observed biomass and WU (RMSE = 1.7, 2.0 and 3.1 kg mm^{-1} ha^{-1} for FI, DI and RF conditions, respectively) (Table 9.4). The calculated WUEb from model simulated biomass and WU showed that there was an under-estimation of WUEb under RF (14.9%) and DI (10.8%) conditions. The model could simulate biomass within an acceptable range; but it over-estimated WU under RF and DI conditions relative to biomass production. However, this was considered acceptable due to observed low RMSE (3.1 and 2.0 kg mm^{-1} ha^{-1}) relative to mean values of calculated WUEb (8.8 and 8.2 kg mm^{-1} ha-1) for model simulation. The calculated WUEb from model simulated biomass and WU showed the model under-estimated (-11.0%) WUEb of the sorghum-cowpea intercrop system under FI conditions; this was also considered as acceptable due to the low RMSE (1.7 kg mm^{-1} ha^{-1}). Over-estimation of WUEb was attributed to under-estimation of WU relative to biomass produced. The sensitivity of WUE to biomass production highlights the importance of accurately simulating it as it has downstream effects on calculation of water related indices.

Table 9.4: Test output of APSIM model for sorghum and cowpea showing observed and simulated values for water use (mm) and biomass yield (kg ha^{-1}) and water use efficiency for biomass (combined sorghum and cowpea), and statistical output for its evaluation.

Water regime	Parameter	Simulated	Observed	RMSE	% Difference[1]
Rainfed	Crop water use (mm)	306.3	330.4	24.1	7
	Biomass yield (kg ha^{-1})	6309.3	5795.0	514.3	15
	WUE (kg mm^{-1})	20.6	17.5	3.0	-15
Deficit irrigation	Crop water use (mm)	353.4	361.5	8.1	2
	Biomass yield (kg ha^{-1})	6506.6	5940.1	37.4	4
		18.4	16.4	2.0	-11
Full irrigation	Crop water use (mm)	391.7	383.6	8.2	-2.
	Biomass yield (kg ha^{-1})	5911.2	6424.5	36	3
	WUE (kg mm^{-1} ha^{-1})	15.1	16.8	1.7	11

[1]% Difference is relative to observed value.

9.4 Conclusions

The APSIM model could simulate sorghum–cowpea intercrop system under different water regimes. The model gave reliable simulations of phenology, biomass, yield and crop water use for both sorghum and cowpea under the different water regimes. Local adaptation of phenology and RUE coefficients proved to be useful in improving model simulations under the different water regimes. Simulations of biomass, yield and WU for sorghum–cowpea under rainfed conditions were overestimated and this resulted in a reduction of calculated WUEb. APSIM was limited in its ability to simulate under rainfed conditions. The model should use a dual approach of both RUE and transpiration efficiency to calculate biomass to improve simulations under water scarce areas. The model gave poor simulations of canopy development parameters leaf number and LAI. Improvements in model performance can be enhanced if it is able to capture extreme weather events. This will increase its applicability as a tool in risk management. APSIM can be used to come up with viable irrigation management strategies for sorghum-cowpea intercrop systems.

References

Asseng, S., Keating, B.., Fillery, I.R.., Gregory, P.., Bowden, J.., Turner, N.., Palta, J.., Abrecht, D.., 1998. Performance of the APSIM-wheat model in Western Australia. F. Crop. Res. 57, 163–179. doi:10.1016/S0378-4290(97)00117-2

Baker, J., Reddy, V.R., 2001. Temperature Effects on Phenological Development and Yield of Muskmelon. Ann. Bot. 87, 605–613. doi:10.1006/anbo.2001.1381

Balwinder-Singh, Gaydon, D.S., Humphreys, E., Eberbach, P.L., 2011. The effects of mulch and irrigation management on wheat in Punjab, India—Evaluation of the APSIM model. F. Crop. Res. 124, 1–13. doi:10.1016/j.fcr.2011.04.016

Basso, B., Cammarano, D., Carfagna, E., 2013. Review of Crop Yield Forecasting Methods and Early Warning Systems 1–56.

Boote, K.J., Jones, J.W., Pickering, N.B., 1996. Potential Uses and Limitations of Crop Models. Agron. J. 88, 704–716. doi:10.2134/agronj1996.00021962008800050005x

Carberry, P.S., Adiku, S.G.K., McCown, R.L., Keating, B.A., 1996. Application of the APSIM cropping systems model to intercropping systems, in: Dynamics of Roots and Nitrogen in Cropping Systems of the Semi-aridArid Tropics. Japan International Research Center for Agricultural Sciences, Tsukuba, Japan, pp. 637–648.

Carberry, P.S., Hochman, Z., Hunt, J.R., Dalgliesh, N.P., McCown, R.L., Whish, J.P.M., Robertson, M.J., Foale, M.A., Poulton, P.L., van Rees, H., 2009. Re-inventing model-based decision support with Australian dryland farmers. 3. Relevance of APSIM to commercial crops. Crop Pasture Sci. 60, 1044. doi:10.1071/CP09052

Cheeroo-Nayamuth, F.., Robertson, M.., Wegener, M.., Nayamuth, A.R.., 2000. Using a simulation model to assess potential and attainable sugar cane yield in Mauritius. F. Crop. Res. 66, 225–243. doi:10.1016/S0378-4290(00)00069-1

Chikowo, R., Corbeels, M., Mapfumo, P., Tittonell, P., Vanlauwe, B., Giller, K.E., 2009. Nitrogen and phosphorus capture and recovery efficiencies, and crop responses to a range of soil fertility management strategies in sub-Saharan Africa. Nutr. Cycl. Agroecosystems 88, 59–77. doi:10.1007/s10705-009-9303-6

Chikowo, R., Zingore, S., Snapp, S., Johnston, A., 2014. Farm typologies, soil fertility variability and nutrient management in smallholder farming in Sub-Saharan Africa. Nutr. Cycl. Agroecosystems 100, 1–18. doi:10.1007/s10705-014-9632-y

Chimonyo, V.G.P., A.T. Modi, and T. Mabhaudhi. 2016. Water use and productivity of a sorghum-cowpea-bottle gourd intercrop system. Agric. Water Manag. 165: 82–96.

Connolly-Boutin, L., Smit, B., 2015. Climate change, food security, and livelihoods in sub-Saharan Africa. Reg. Environ. Chang. doi:10.1007/s10113-015-0761-x

Cooper, P.J.M., Dimes, J., Rao, K.P.C., Shapiro, B., Shiferaw, B., Twomlow, S., 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? Agric. Ecosyst. Environ. 126, 24–35. doi:10.1016/j.agee.2008.01.007

Dimes, J., Achien, J., Mesfin, T., Abeya, T., Makoko, B., Nhantumbo, N., Rodriguez, D., 2011. Evaluation of APSIM to simulate maize-bean cropping systems in eastern and southern Africa: an alternative approach, in: 5th World Congress on Conservation Agriculture and Farming Systems Design. Australian Centre for International Agricultural Research, pp. 1 – 4.

Fuad-Hassan, A., Tardieu, F., Turc, O., 2008. Drought-induced changes in anthesis-silking interval are related to silk expansion: A spatio-temporal growth analysis in maize plants subjected to soil water deficit. Plant, Cell Environ. 31, 1349–1360. doi:10.1111/j.1365-3040.2008.01839.x

Garrido, M., Román, L., Silva, P., Castellaro, G., Cortázar, V.G. De, 2013. Characterization of genetic coefficients of durum wheat (Triticum turgidum L . ssp . Chil. J. Agric. Res. 73, 91–98. doi:10.4067/S0718-58392013000200002.2007

Gowing, J.W., Palmer, M., 2008. Sustainable agricultural development in sub-Saharan Africa: the case for a paradigm shift in land husbandry. Soil Use Manag. 24, 92–99. doi:10.1111/j.1475-2743.2007.00137.x

Grenz, J.H., Manschadi, A.M., deVoil, P., Meinke, H., Sauerborn, J., 2006. Simulating crop–parasitic weed interactions using APSIM: Model evaluation and application. Eur. J. Agron. 24, 257–267. doi:10.1016/j.eja.2005.10.002

Hammer, G.L., van Oosterom, E., McLean, G., Chapman, S.C., Broad, I., Harland, P., Muchow, R.C., 2010. Adapting APSIM to model the physiology and genetics of complex adaptive traits in field crops. J. Exp. Bot. 61 , 2185–2202. doi:10.1093/jxb/erq095

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288. doi:http://dx.doi.org/10.1016/S1161-0301(02)00108-9

Kim, H.K., van Oosterom, E., Dingkuhn, M., Luquet, D., Hammer, G., 2010. Regulation of tillering in sorghum: environmental effects. Ann. Bot. 106, 57–67. doi:10.1093/aob/mcq079

Kiniry, J., Jones, C., O'toole, J., Blanchet, R., Cabelguenne, M., Spanel, D.A., 1989. Radiation-use efficiency in biomass accumulation prior to grain-filling for five grain-crop species. F. Crop. Res. 20, 51–64. doi:10.1016/0378-4290(89)90023-3

Knörzer, H., Lawes, R., 2011. Evaluation and performance of the APSIM crop growth model for German winter wheat, maize and fieldpea varieties in monocropping and intercropping. J. Agric. Sci. Technol.

Lambin, E.., Rounsevell, M.D.., Geist, H.., 2000. Are agricultural land-use models able to predict changes in land-use intensity? Agric. Ecosyst. Environ. 82, 321–331. doi:10.1016/S0167-8809(00)00235-8

Legates, D., McCabe, G., 1999. Evaluating the use of“ goodness-of-fit” measures in hydrologic and hydroclimatic model validation. Water Resour. Res. 35, 233 – 241.

Littleboy, M., Freebairn, D., Silburn, D., 1999. A Computer Simulation Model of Productivity Erosion Runoff Functions to Evaluate Conservation Techniques (PERFECT). Queens Department of Primary Industries Bulletin, QB89005.

Lobell, D.B., Cassman, K.G., Field, C.B., 2009. Crop Yield Gaps: Their Importance, Magnitudes, and Causes. Annu. Rev. Environ. Resour. 34, 179–204. doi:10.1146/annurev.environ.041008.093740

Luo, Z., Wang, E., Fillery, I.R.P., Macdonald, L.M., Huth, N., Baldock, J., 2014. Modelling soil carbon and nitrogen dynamics using measurable and conceptual soil organic matter pools in APSIM. Agric. Ecosyst. Environ. 186, 94–104. doi:10.1016/j.agee.2014.01.019

McCown, R.L., Carberry, P.S., Hochman, Z., Dalgliesh, N.P., Foale, M.A., 2009. Re-inventing model-based decision support with Australian dryland farmers. 1. Changing intervention concepts during 17 years of action research. Crop Pasture Sci. 60, 1017. doi:10.1071/CP08455

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P., Freebairn, D.M., 1996. APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. Agric. Syst. 50, 255–271. doi:10.1016/0308-521X(94)00055-V

McMaster, G., Wilhelm, W., 1997. Growing degree-days: one equation, two interpretations. Agric. For. Meteorol. 87, 291 – 300.

Moeller, C., Sauerborn, J., Voil, P., Manschadi, A., Pala, M., Meinke, H., 2014. Assessing the sustainability of wheat-based cropping systems using simulation modelling: sustainability. Sustain. Sci. 9, 1–16.

Mohanty, M., Probert, M.E., Reddy, K.S., Dalal, R.C., Mishra, A.K., Subba Rao, A., Singh, M., Menzies, N.W., 2012. Simulating soybean–wheat cropping system: APSIM model parameterization and validation. Agric. Ecosyst. Environ. 152, 68–78. doi:10.1016/j.agee.2012.02.013

Msongaleli, B., Rwehumbiza, F., Tumbo, S.D., Kihupi, N., 2014. Sorghum Yield Response to Changing Climatic Conditions in Semi-aridArid Central Tanzania : Evaluating Crop Simulation Model Applicability 822–833.

Nape, K., 2011. Using Seasonal Rainfall with APSIM to Improve Maize Production in the Modder River Catchment. University of Free State, Bloemfontein.

Ncube, B., Dimes, J.P., van Wijk, M.T., Twomlow, S.J., Giller, K.E., 2009. Productivity and residual benefits of grain legumes to sorghum under semi-aridarid conditions in south-western Zimbabwe: Unravelling the effects of water and nitrogen using a simulation model. F. Crop. Res. 110, 173–184. doi:10.1016/j.fcr.2008.08.001

Nkonya, E., Place, F., Kato, E., Mwanjololo, M., 2015. Climate Risk Management Through Sustainable Land Management in Sub-Saharan Africa, in: Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa. Springer International Publishing, Cham, pp. 75–111. doi:10.1007/978-3-319-09360-4_5

Potgieter, A.B., Hammer, G.L., Doherty, A., de Voil, P., 2005. A simple regional-scale model for forecasting sorghum yield across North-Eastern Australia. Agric. For. Meteorol. 132, 143–153. doi:10.1016/j.agrformet.2005.07.009

Reynolds, M.P., Pietragalla, J., Setter, T.L., Condon, A.G., 2008. Source and sink traits that impact on wheat yoeld and biomass in high production environments, in: Reynolds, M.P., Pietragalla, J., Braun, H.J. (Eds.), International Symposium on Wheat Yield Potential: Challenges to International Wheat Breeding. CIMMYT, pp. 136 – 147.

Rezig, M., Sahli, a, Ben Jeddi, F., Harbaoui, Y., 2010. Adopting intercropping system for potatoes as practice on drought mitigation under Tunisian conditions. Options Méditerranéennes. Séries A. Mediterr. Semin. 329–334.

Robertson, M., Gaydon, D., Latta, R., Peoples, M., Swan, A., 2004. Simulating lucerne/crop companion farming systems in Australia, in: Proceedings of the 4th International Crop Science Congress. (Australian Society of Agronomy: Brisbane).

Seelig, B., Alfonso, J., 2007. GIS Applications in Agriculture. CRC Press.

Sinclair, T.R., and T. Horie. 1989. Leaf Nitrogen, Photosynthesis, and Crop Radiation Use Efficiency: A Review. Crop Sci. 29(1): 90Available at https://dl.sciencesocieties.org/publications/cs/abstracts/29/1/CS0290010090 (verified 21 February 2015)

Tao, F., Yokozawa, M., Xu, Y., Hayashi, Y., Zhang, Z., 2006. Climate changes and trends in phenology and yields of field crops in China, 1981–2000. Agric. For. Meteorol. 138, 82–92. doi:10.1016/j.agrformet.2006.03.014

Tsubo, M., Mukhala, E., Ogindo, H.O., Walker, S., 2003. Productivity of maize-bean intercropping in a semi-aridarid region of South Africa. Water SA 29, 381–388. doi:10.4314/wsa.v29i4.5038

Van Oosterom, E.., Carberry, P., Hargreaves, J.N.., O'Leary, G.., 2001. Simulating growth, development, and yield of tillering pearl millet. F. Crop. Res. 72, 67–91. doi:10.1016/S0378-4290(01)00165-4

Wang, E., Robertson, M.J., Hammer, G.L., Carberry, P.S., Holzworth, D., Meinke, H., Chapman, S.C., Hargreaves, J.N.G., Huth, N.I., McLean, G., 2002. Development of a generic crop model template in the cropping system model APSIM. Eur. J. Agron. 18, 121–140. doi:10.1016/S1161-0301(02)00100-4

Water Research Commission, 2014. Knowledge Review 2013/14. Water Research Commission of South Africa, Gezina, Pretoria.

Willey, R.., 1979. Intercropping-Its importance and research needs.1.Competition and yield advantages. F. Crop Abstr. 32, 1–10.

Willmott, C., 1981. On the validation of models. Phys. Geogr. 2, 184 – 194. doi:10.1080/02723646.1981.10642213 Cort J. Willmott

Yang, C., Huang, G., Chai, Q., Luo, Z., 2011. Water use and yield of wheat/maize intercropping under alternate irrigation in the oasis field of northwest China. F. Crop. Res. 124, 426–432. doi:10.1016/j.fcr.2011.07.013

CHAPTER 10

SORGHUM BEST MANAGEMENT PRACTICES BASED ON AQUACROP PLANTING DATES SCENARIO ANALYSIS

Hadebe, S.T., Modi, A.T. and Mabhaudhi, T.

10.1 Introduction

About 95% of agriculture in sub–Saharan Africa is primarily rainfed (Singh et al., 2011) with about 70% of the population relying on agriculture for food and livelihoods (Livingston et al., 2011). Under these conditions, unfavourable weather conditions due to climate variability and change (Tsheko, 2003) increase the incidence of food insecurity. This negatively affects resource–poor farmers whose livelihoods depend mainly on agriculture (Tadross et al., 2005). In addition, the inability of this group of farmers to adapt to changing or variable weather patterns makes them increasingly vulnerable and prone to repeated episodes of crop failure and food insecurity. For farmers relying on rainfed agriculture, the ability to adapt to changing and/or variable weather patterns on a season–to–season basis is a prerequisite to successful crop production. There are various strategic and tactical decisions that can allow farmers to adapt to changing and variable weather patterns. On a tactical level, these include crop or cultivar choice and planting date selection.

Traditionally, farmers use the onset of the rainy season as the criteria for setting planting dates. However, there is much variation as to how resource-poor farmers define this criterion. This often results in farmers experiencing mixed fortunes and making them inflexible as their criteria seldom changes from season to season. Onset of rainy season has become unpredictable and mostly delayed over the past decades (Leary et al., 2008; Loo et al., 2014; Patwardhan et al., 2014). Onset of rainfall is one of the most important occurrences for the farmer. Early onset allows farmers to plough the land and plant early and benefit from low evaporative demand, while late onset can result in crop sensitive stages coinciding with unfavourable periods (Moeletsi et al., 2011). The start and end of the rainy season define the length of the rainy season, which strongly determines the success, or failure of rainfed crops. In addition, the quality of the growing season, as indicated by the length and severity of within-season dry spells, will also influence the yield gap and can often cause total crop failure (Geerts et al., 2006).

It is therefore important to determine, with reasonable accuracy, the probability levels of the onset of rains, cessation of rains and length of rainy period, as well as their inter-relationships, to assist in planning of dryland farming activities (Moeletsi and Walker, 2012). Informed decision making for optimum management practices such as cultivar choice, planting dates and fertiliser application rates can contribute to increased yields under rainfed conditions. Optimum management practices can be evaluated using validated models as within–season and seasonal decision support tools (Boote et al., 1996; Kang et al., 2009; Lobell and Burke, 2010). In the current study, an established water–driven model, AquaCrop (Steduto et al., 2009; Raes et al., 2009), was applied for a range of agro–ecologies across KwaZulu–Natal to assist with generating best practice management recommendations for cultivar choice and planting date selection.

10.2 Materials and Methods

10.2.1 Study site descriptions

Three agro-ecologies (Deepdale, Richards Bay and Ukulinga) across KwaZulu–Natal province were selected based on access to and differences in long–term meteorological data and soil information (Table 10.1). Daily data for Ukulinga meteorological parameters was obtained from an on–farm (within 100 m radius) automatic weather station courtesy of Agricultural Research Council – Institute for Soil, Climate and Water (ARC–ISCW). Daily meteorological data for Deepdale and Richards Bay were obtained courtesy of the South African Sugar Research Institute (SASRI) weather station located within a 10 km radius from field trial agro-ecologies. Weather data obtained were minimum and maximum temperature, rainfall, and reference evapotranspiration. Weather parameters obtained were used to create climate files and input into AquaCrop.

10.2.2 Model parameterisation

Simulations were performed using AquaCrop (Version 4.1). Climate files for each of the selected agro–ecologies were developed using daily weather data for maximum and minimum temperatures, rainfall and reference evapotranspiration. Long–term weather data for each of the agro–ecologies were obtained via the ARC–ISCW and SASRI network of automatic weather stations. These were then used to develop separate temperature (.TMP), rainfall (.PLU) and reference evapotranspiration (.ETO) files in AquaCrop. For CO_2, AquaCrop's default CO_2 file measured at Mauna Luau was used; thereafter, climate files (.CLI) were developed for each agro–ecology and input into the model.

Table 10.1: Soil and climate descriptions for the three agro–ecological zones.

	Deepdale	**Richards Bay**	**Ukulinga**
Geographical location	28º01'S; 28º99'E	28°19'S; 32°06E	29º37'S; 30º16'E
Altitude (m a.s.l.)	998	30	775
Bio-resource group	Coast hinterland thornveld	Moist coast forest, thorn and palmveld	Moist coast hinterland and ngongoni veld
Annual rainfall	750 – 850 mm	820 – 1423 mm	694 mm
Average temperature	18.4°C	22°C	17°C
Frost occurrence	Moderate	None	Light and occasional
Soil texture class	Clay	Sand	Clay
Clay content	53%	< 5%	< 29%
Soil type	Jonkersberg form (Jb)	Inhoek form (Ik)	Chromic luvisols
Field capacity (%)	46.2	10.9	46.3
Permanent wilting point (%)	34.7	6.2	23
Saturation (%)	50	47.1	46.7
Soil profile depth (m)	>1	>1	0.6

AquaCrop already has a default sorghum crop file. For the current study, the default file was fine–tuned to develop two separate sorghum crop files (.CRO) for PAN8816 and Ujiba sorghum. Fine-tuning was done using data derived from field trials conducted during 2013/14 season at Ukulinga Research Station. Briefly, Ujiba is a landrace of which rural farmers usually prefer them for production because they do not have to repurchase seed every year. PAN8816 is a hybrid variety preferred for production by commercial farmers. Details of model parameterisation and testing were reported in Chapter 6. Thereafter, the crop files were input into the AquaCrop database.

Similar to other established models, AquaCrop requires a detailed soil file for the selected location. Soil files (.SOL) for each of the selected agro–ecologies were developed using information described in Table 10.1 and input into AquaCrop.

10.2.3 Development of planting scenarios in AquaCrop

AquaCrop was used to develop planting scenarios according to Mizha et al. (2014). First sorghum planting occurs around the first week of September in KwaZulu–Natal, soon after the first spring rains. Latest planting usually occurs by end of January (Mlambo 2014; Nkala 2014 *Personal communication*). The Department of Agriculture, Forestry and Fisheries (DAFF, 2010) recommends optimal planting time for sorghum from start of November until end of December in South Africa, with dates falling on either side of the recommended times regarded as early and late planting, respectively. The first planting date can be defined as the first rainfall event capable of supporting germination (Keatinge et al., 1995). All simulation runs were started on the first day of September in each season, before the start of the rainfall season and assuming a bare soil. In this study, the first planting date of the season was defined according to the Agricultural Research and Extension (AREX) criterion (Raes et al., 2004) which defines a planting date as the occurrence of 25 mm rainfall in 7 days after the initial search date, the first planting date in this case (Mizha et al., 2014). This ensures there is enough soil water, not only for germination but also to sustain the crop through the early development stage (Moeletsi and Walker, 2012).

As a result of variability in rainfall amount, distribution and subsequently onset of rainfall season, the number and spread of planting days generated by AquaCrop varied across agro-ecologies. For purposes of the current study, at most ten planting dates per site with an average two planting dates per month, were used for model scenario analyses (Table 10.2).

10.2.4 Model simulations

Climate, crop and soil files were input into AquaCrop Version 4.1. Management file was set to run for rainfed crop production. Planting dates were varied based on times generated by the model using user-defined criteria as described in above. Thereafter, model runs were performed.

10.2.5 Model evaluation

Model inputs for weather and model outputs were analysed using GenStat® (Version 16, VSN International, UK) as well as using descriptive statistics and Box and whisker plots computed using Microsoft Excel®.

Table 10.2: AquaCrop simulated planting dates using AREX criteria for three different agro-ecologies.

Planting date number	Deepdale	Richards Bay	Ukulinga
1	29 October	15 September	7 September
2	19 November	29 September	26 September
3	1 December	18 October	22 October
4	7 December	18 November	27 October
5	12 December	23 November	11 November
6	21 December	29 November	24 November
7	25 December	23 December	10 December
8	1 January	2 January	20 December
9	3 January	3 January	10 January
10	11 January	30 January	15 January

10.3 Results and Discussion

10.3.1 Fitting sorghum into different agro-ecologies

Rainfall received during the growing period, as simulated by AquaCrop, varied significantly ($P<0.001$) between planting dates across different agro-ecologies. For the simulated agro–ecologies, Ukulinga received high rainfall for all simulated planting dates followed by Deepdale and Richards Bay, respectively (Table 10.3). Differences in biomass, yield, harvest index and water productivity were highly significant ($P<0.001$) between individual agro-ecologies. AquaCrop separates water use [evapotranspiration (ET)] into transpiration (T) and soil evaporation I. In terms of plant growth and biomass production, transpiration is productive water loss as it is directly exchanged for biomass, while evaporation represents unproductive water loss (Mabhaudhi et al., 2014). Water losses to soil evaporation at Ukulinga (154 – 224.6 mm) and Richards Bay (136.6 – 210.1 mm) were higher than water transpired (130.9 – 209.4 and 36.7 – 88.8 mm). The opposite was true for Deepdale where transpiration (Table 10.5) was higher than evaporative water losses (Table 10.4); this translated to significantly ($P<0.001$) higher biomass and yield compared to Ukulinga and Richards Bay, respectively. High variability in rainfall, soil evaporation and transpiration at Richards Bay resulted in low and irregular yields as well as low water productivity (Fig 10.1). Consequently, there was a higher frequency of crop failure for Richards Bay compared to Ukulinga and Deepdale agro–ecologies were there was no crop failure (Fig 10.3 and 10.4).

From the results of this study, production of sorghum is suited for Deepdale and Ukulinga agro-ecologies. There is adequate rainfall received during the growing period in Richards Bay (372.3 mm) for production of sorghum, however high evaporation losses (183.3 mm) resulted in low yield and crop failure (Fig 10.3 and 10.4) making Richards Bay unsuitable for sorghum production. High losses due to evaporation at all agro-ecologies can be significantly reduced using water retention, capture and storage strategies. Soil water retention strategies such as low tillage and mulching farming practices are recommended to reduce soil evaporation. Transpired water (<265 mm) in all agro-ecologies was a far cry from sorghum crop water requirements of 450–650 mm (FAO, 1991; Hensley et al*.,* 2000; Jewitt et al*.,* 2009), indicating that considerable and significant sorghum yield improvement can be achieved through effective irrigation using soil and rain water. Investing in rainwater harvesting infrastructure is a key element for all agro-ecologies to capture excess rainwater, especially for sorghum farming in Richards Bay where transpiration is low.

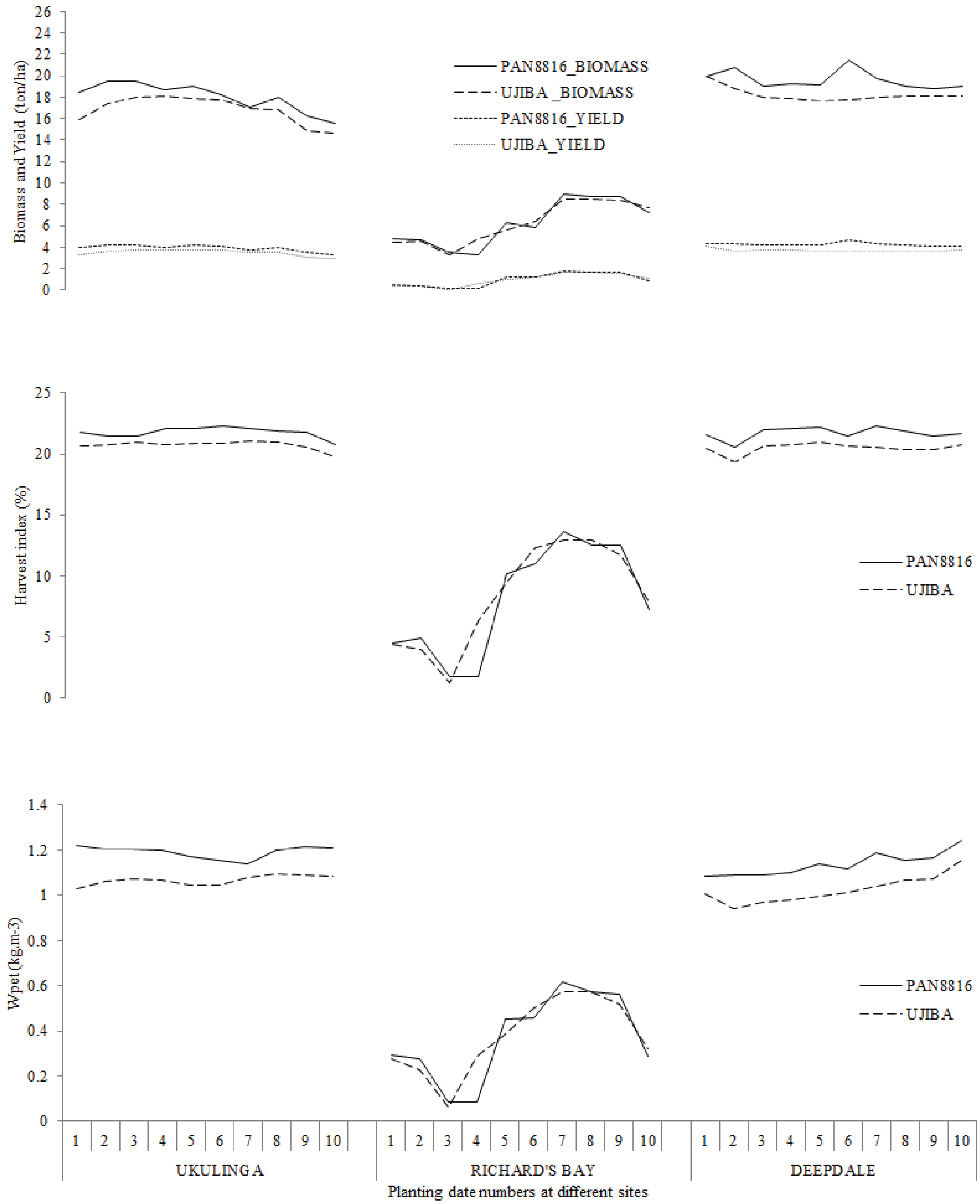

Figure 10.1: Mean simulated biomass and yield (A), percentage harvest index (B) and water productivity (C) for 10 planting dates at each of three agro-ecologies.

Table 10.3: Mean rainfall received during the growing season over a ten year period (2003–2013) for the three agro–ecologies. Rainfall is based on modelled output for rainfall received during the growing season.

Variety	Planting date	Ukulinga		Richards Bay		Deepdale	
		Mean	*SD	Mean	SD	Mean	SD
		(mm)					
PAN8816	1	507.1	88.2	269.6	98.7	543.0	67.7
	2	540.0	78.4	331.9	102.9	523.3	63.2
	3	535.7	85.5	335.7	130.6	478.6	73.0
	4	539.3	95.6	357.3	113.9	458.9	74.9
	5	525.0	229.2	364.2	124.2	433.2	71.5
	6	491.9	94.4	367.4	131.0	406.4	59.7
	7	445.3	115.3	421.3	199.5	394.1	66.6
	8	418.9	104.7	419.4	180.1	369.6	69.6
	9	335.7	103.3	450.2	184.7	343.9	61.2
	10	327.6	104.0	469.0	158.1	323.0	72.2
Ujiba	1	528.6	91.1	269.6	98.6	534.7	66.6
	2	559.5	77.5	302.2	106.2	517.1	62.7
	3	552.9	96.1	313.9	162.7	474.0	75.3
	4	548.0	96.5	313.9	113.9	456.2	72.8
	5	534.9	89.3	364.2	124.2	429.0	67.8
	6	500.3	105.7	367.4	131.0	403.9	60.8
	7	447.1	118.0	421.3	189.7	386.5	66.8
	8	420.7	103.8	419.4	180.1	357.9	68.8
	9	342.2	106.6	419.3	180.9	350.2	66.4
	10	312.1	100.8	469.0	158.1	317.4	64.7

*SD = standard deviation

Table 10.4: Simulated mean soil evaporation for PAN8816 and Ujiba sorghum varieties over a ten-year period (2003–2013) for three agro-ecologies.

Variety	Planting date	Ukulinga		Richards Bay		Deepdale	
		Mean	*SD	Mean (m)	SD	Mean	SD
		(mm)					
PAN8816	1	225.6	33.8	136.3	20.5	223.6	15.9
	2	227.7	15.4	169.1	25.2	221.7	27.5
	3	231.4	12.9	173.2	28.7	214.4	26.1
	4	230.3	16.1	186.4	47.0	208.3	27.8
	5	229.2	21.9	186.9	49.2	194.6	29.6
	6	238.2	59.0	186.2	53.7	192.0	26.7
	7	204.3	14.0	194.7	60.7	185.0	20.8
	8	191.4	13.0	199.1	62.8	180.0	18.2
	9	166.9	14.3	205.8	66.6	167.7	17.1
	10	160.1	11.4	210.1	39.0	156.1	196.0
Ujiba	1	224.2	39.6	136.3	20.5	233.1	14.9
	2	220.5	20.30	155.5	24.8	230.1	27.7
	3	222.6	13.2	162.7	27.3	223.2	26.3
	4	222.2	16.6	186.4	31.2	218.6	27.0
	5	221.4	24.0	186.9	49.2	213.6	30.8
	6	232.1	64.5	186.2	53.7	200.8	27.1
	7	195.0	15.0	194.7	60.7	192.0	22.1
	8	182.9	12.9	199.1	62.8	172.0	18.6
	9	169.4	18.3	199.9	61.9	175.4	19.3
	10	154.0	26.2	210.1	39.0	153.4	15.3

*SD = standard deviation

Table 10.5: Simulated mean crop transpiration for PAN8816 and Ujiba sorghum varieties over a ten-year period (2003-2013) for three agro–ecologies.

Variety	Planting date	Ukulinga		Richards Bay		Deepdale	
		Mean	*SD	Mean	SD	Mean	SD
		(mm)					
PAN8816	1	174.1	48.2	42.9	37.1	261.6	19.7
	2	190.9	32.5	46.5	37.4	237.7	32.3
	3	193.8	16.2	36.7	25.4	233.5	38.4
	4	194.8	16.1	53.6	54.4	218.6	35.9
	5	188.7	20.6	62.2	59.2	214.7	36.1
	6	162.0	59.7	70.3	62.8	209.6	25.2
	7	168.1	18.8	87.2	79.3	209.1	25.2
	8	163.9	17.2	86.4	81.8	195.1	14.5
	9	131.2	27.5	88.8	85.4	202.1	18.2
	10	125.5	23.9	80.6	77.1	196.0	20.7
Ujiba	1	188.4	54.6	42.9	37.1	243.5	18.1
	2	206.7	40.0	46.5	37.4	221.8	29.1
	3	209.3	17.5	36.8	24.9	208.2	34.7
	4	209.4	17.6	36.8	33.2	203.0	34.1
	5	200.9	22.6	62.2	59.2	198.9	34.4
	6	174.2	64.3	70.3	62.8	196.9	27.1
	7	179.9	22.0	87.2	79.3	197.2	22.4
	8	174.9	19.1	86.4	81.7	202.6	18.6
	9	142.8	29.7	85.9	81.2	190.0	17.3
	10	130.9	26.2	80.6	77.1	188.5	16.4

*SD = standard deviation

10.3.2 Effect of planting date selection on water use, biomass and yield of sorghum

Evaporation and transpiration significant ($P<0.001$) varied between planting dates which resulted in considerable differences ($P<0.001$) all four yield related parameters between individual planting dates in all agro-ecologies. Uneven and erratic rainfall distribution (Table 10.3) across planting dates accounted for differences in evaporation and transpiration.

Optimal planting dates at Ukulinga are between 7 September and 24 November as highest, stable yields (Fig 10.2 and 10.3) are achieved during the period. Planting later than these dates decreased biomass, yield and water productivity (Fig 10.1) and stability (Fig 10.2, 10.3 and 10.5) thereof. However, reasonable biomass (> 14 ton ha^{-1}) and yields (> 3 ton ha^{-1}) were achieved when planting later than optimal planting dates. Despite low observed yield and water use traits at Richards Bay, optimal sorghum yields were achieved when planting between 23 December and 3 January. Yields were unstable throughout planting dates at Richards Bay with high crop failure frequency, due to low irregular rainfall, high evaporation and low transpiration experienced by crops. In Deepdale, optimal planting time was achieved throughout simulated planting time, as yield and biomass were high and stable. Yield and water productivity were most stable when planting between 21 December and 3 January in Deepdale. Challenges of irregular and erratic rainfall on all planting dates can be mitigated by using long– and short–term water capture and storage strategies to capture and better use excess rainfall from storm events. Rainfall must be retained by techniques that reduce storm-water runoff, improve infiltration and increase the water storage capacity of the soil. Strategies that can help reduce runoff through improved infiltration capacity and soil transmission characteristics are: mulch farming, soil conditioning, and ploughing methods that keep the upper soil layers porous at least for a short time especially in compact soils that restrict root development and infiltration. On planting dates where yields are highly unstable and where a deficit exists in crop water requirements, supplementary irrigation using harvested rainwater and other external water sources should be explored to mitigate the challenge of insufficient transpired water.

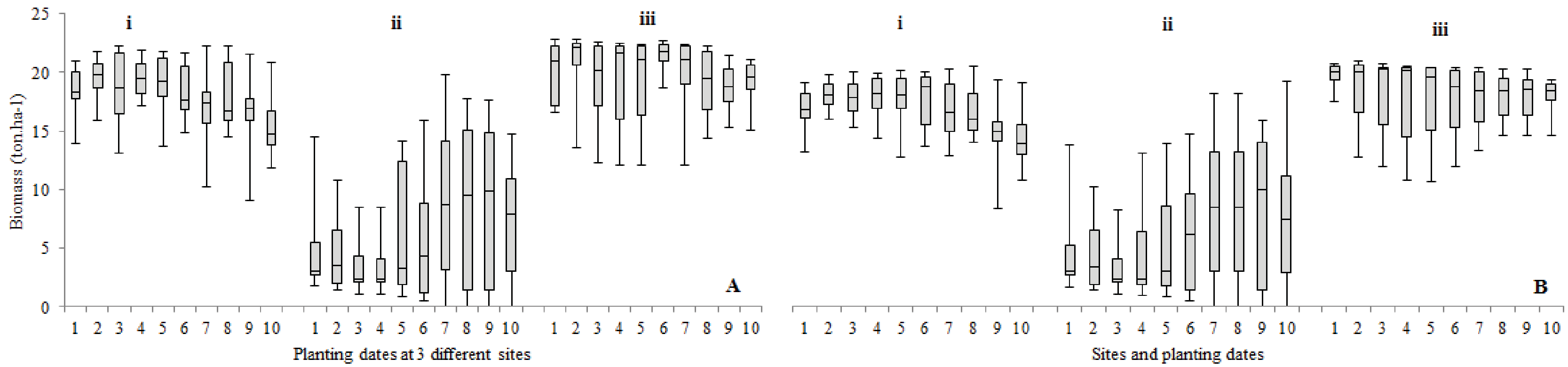

Figure 10.2: Biomass distribution for PAN8816 (A) and Ujiba (B) sorghum varieties simulated using AquaCrop for 10 planting dates at each of 3 agro-ecologies (i) Ukulinga, (ii) Richards Bay and (iii) Deepdale. Boxes delimit the inter-quartile range (25–75 percentiles) and whiskers show the high and low extreme values.

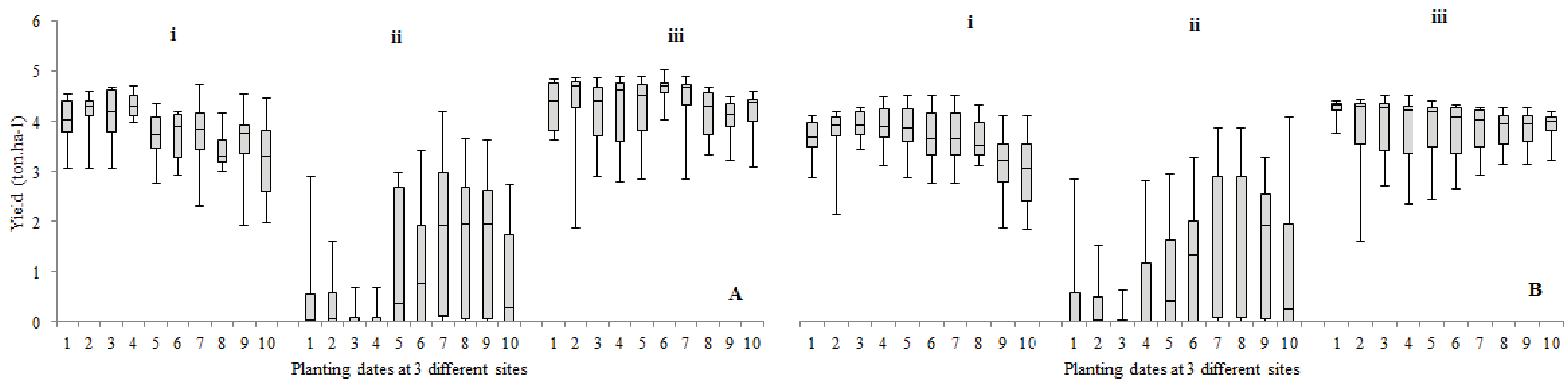

Figure 10.3: Yield distribution for PAN8816 (A) and Ujiba (B) sorghum varieties simulated using AquaCrop for 10 planting dates at each of 3 agro-ecologies (i) Ukulinga, (ii) Richards Bay and (iii) Deepdale. Boxes delimit the inter-quartile range (25–75 percentiles) and whiskers show the high and low extreme values.

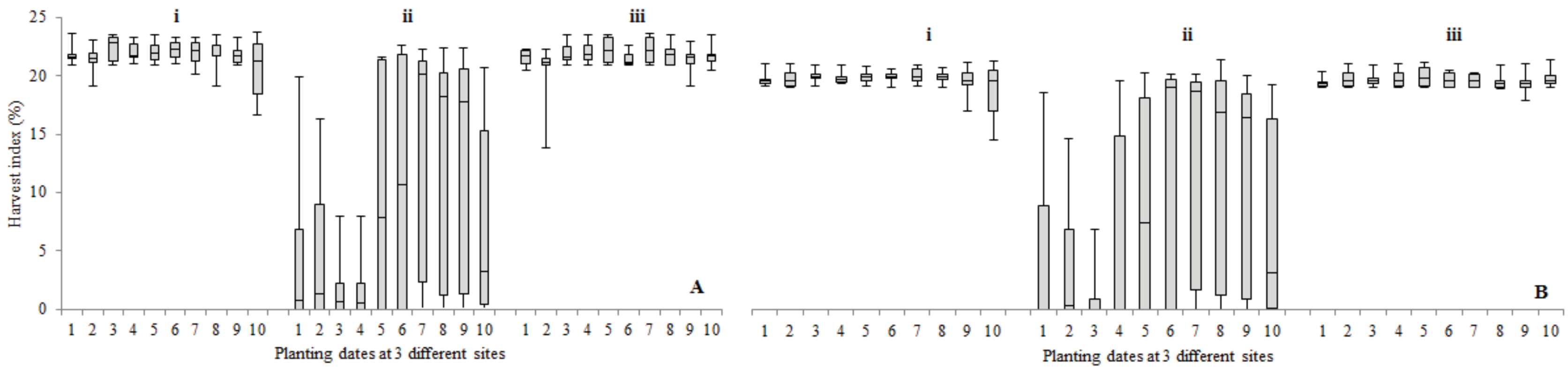

Figure 10.4: Harvest index distribution for PAN8816 (A) and Ujiba (B) sorghum varieties simulated using AquaCrop for 10 planting dates at each of 3 agro-ecologies (i) Ukulinga, (ii) Richards Bay and (iii) Deepdale. Boxes delimit the inter-quartile range (25–75 percentiles) and whiskers show the high and low extreme values.

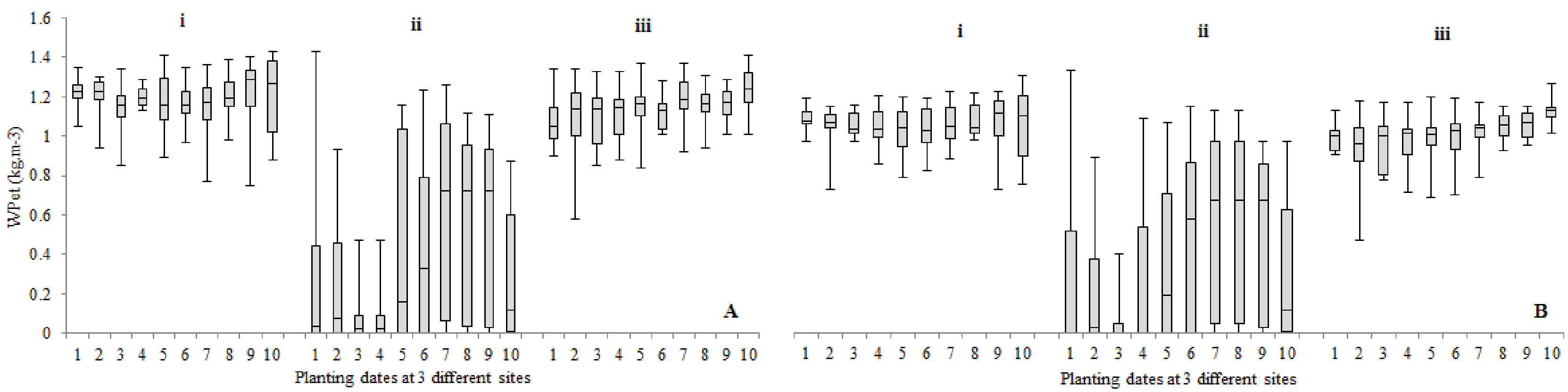

Figure 10.5: Water productivity (WPet) distribution for PAN8816 (A) and Ujiba (B) sorghum varieties simulated using AquaCrop for 10 planting dates at each of 3 agro-ecologies (i) Ukulinga, (ii) Richards Bay and (iii) Deepdale. Boxes delimit the inter-quartile range (25–75 percentiles) and whiskers show the high and low extreme values.

10.3.3 Yield and water use responses of sorghum varieties to agro-ecologies and planting dates. Evaporation and transpiration were similar ($P>0.05$) between PAN8816 and Ujiba sorghum varieties. This resulted in similar ($P>0.05$) biomass, yield, harvest index and water productivity in both varieties across planting dates and agro-ecologies. PAN8816 benefitted marginally from early emergence, high canopy cover and delayed senescence; this translated to higher biomass, yield, harvest index and water productivity (Fig 10.1) compared to Ujiba. Affording farmers can plant PAN8816 to benefit from higher yields, while resource–constrained farmers are recommended to grow Ujiba as yield losses are not significant when planting Ujiba as an alternative.

10.4 Possible Management Practices and Conclusions

- Transpired water (<265 mm) in all planting dates and production site scenarios was a far cry from sorghum crop water requirements (450 – 600 mm) which indicates that considerable yield improvement can be achieved through effective capture, storage, supplementary irrigation and reuse of rainfall water. Rainwater harvesting can be used to capture rainfall during and outside the growing season. Richards Bay sorghum farmers would benefit most from such strategies, as transpiration was low throughout planting dates, water scarcity linked crop failure occurred frequently and the agro-ecology has a longer rainfall season.
- Sorghum farmers in Deepdale and Ukulinga can explore increasing planting population to exploit evaporated water. Increasing planting population however increases demand of soil nutrients and minerals, therefore appropriate soil fertilisation mechanisms are recommended with this strategy. In Richards Bay, farmers need not consider this strategy but focus on strategies that increase transpiration. Intercropping sorghum with a legume is recommended to effectively use evaporative water in all three agro-ecologies. Ideally, the legume of choice should have low water requirements and a short growing (≈90 days) season.
- Different levels of mulching and low tillage farming practices are suggested to conserve soil moisture and increase soil cover. Extent at which each strategy is used largely depends on rainfall per growing season and evaporation, which differ per agro-ecology and planting date. This strategy is especially recommended when farming sorghum outside optimal planting dates discussed in this study.

- Rainfall must be retained by techniques that reduce storm-water runoff, improve infiltration and increase the water storage capacity of the soil. Strategies that can help reduce runoff through improved infiltration capacity and soil transmission characteristics are: mulch farming, soil conditioning, and ploughing methods that keep the upper soil layers porous at least for a short time especially in compact soils that restrict root development and infiltration
- Contour farming, ridge and mound tillage, strip farming and terrace farming are options that are suggested to reduce run-off during extreme rainfall events.

References

Chinweze, C., 2015. Biofuels and Food Security in Sub-Saharan Africa. GRF Davos Planet@Risk, Special Issue on the 5th IDRC Davos 2014 3(1), 137–139.

Food and Agriculture Organisation (FAO), 1991. A manual for the design and construction of water harvesting schemes for plant production, in: Critchley, W., Siegert, K., (Eds). Water harvesting (AGL/MISC/17/91).

Geerts, S., Raes, D., Garcia, M., Del Castillo, C., Buytaert, W., 2006. Agro-climatic suitability mapping for crop production in the Bolivian Altiplano: a case study for quinoa. Agric. Forest Meteorol. 139, 399– 412.

Hensley, M., Botha, J.J., Anderson, J.J., van Staden, P.P., Du Toit, A., 2000. Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water. WRC Report No. 878/1/00. Water Research Commission, Pretoria, South Africa.

Intergovernmental Panel on Climate Change (IPCC), 2014. Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, in: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L., (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1-32.

Jewitt, G.W.P., Wen, H.W., Kunz, R.P., van Rooyen, A.M., 2009. Scoping Study on Water Use of Crops/Trees for Biofuels in South Africa. Water Research Commission (WRC) report no. 1772/1/09.

Kang, Y., Khan, S., Ma, S., 2009. Climate change impacts on crop yield, crop water productivity and food security – A review. Progress Natur. Sci. 19(12), 1665–1674.

Livingston, G., Schonberger, S., Delaney, S., 2011. Sub-Saharan Africa: The state of smallholders in agriculture. Conference on new directions for smallholder agriculture. IFAD, Rome, Italy.

Lobell, D.B., Burke, M.B., 2010. On the use of statistical models to predict crop yield responses to climate change. Agric. Forest Meteorol. 150 (11), 1443–1452.

Mabhaudhi, T., Modi, A.T., Beletse, Y.G., 2014. Parameterisation and evaluation of the FAO–AquaCrop model for a South African taro (*Colocasia esculenta* L. Schott) landrace. Agric. Forest Meteo. 132–139.

Mhizha, T., Geerts, S., Vanuytrecht, E., Makarau, A., Raes, D., 2014. Use of the FAO AquaCrop model in developing sowing guidelines for rainfed maize in Zimbabwe. Water SA 40, 233–244.

Moeletsi, M.E., Walker, S., Landman, W.A., 2011. ENSO and implications on rainfall characteristics with reference to maize production in the Free State Province of South Africa. Phys. Chem. Earth 36, 715–726.

Moeletsi, M.E., Walker, S., 2012. Rainy season characteristics of the Free State Province of South Africa with reference to rain-fed maize production. Water SA 38(5), 775–782.

Raes, D., Sithole, A., Makaru, A., Millford, J., 2004. Evaluation of first planting dates recommended by criteria currently used in Zimbabwe. Agric. Forest Meteo. 125, 177–185.

Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2009. AquaCrop–The FAO crop model to simulate yield response to water: II. Main algorithms and soft ware description. Agron. J. 101, 438–447.

Singh, P., Wani, S.P., Pathak, P., Sahrawat, K.L., Singh, A.K., 2011. Increasing crop productivity and effective use of water in rainfed agriculture, in: Integrated watershed management in rainfed agriculture. CRC Press (Taylor and Francis), London, UK. Pp 315–347.

Steduto, P., Hsiao, T.C., Raes, D., Fereres, E., 2009. AquaCrop–The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agron. J. 101, 426–437.

Tadross, M.A., Hewiston, B.C., Usman, M.T., 2005. The interannual variability of the onset of the maize growing season over South Africa and Zimbabwe. J. Climate 18, 3356–3372.

Tsheko, R., 2003. Rainfall reliability, drought and flood vulnerability in Botswana. Water SA 29(4), 389–392.

Water Research Commission (WRC), 2014. WRC Knowledge Review 2013/14. Project No. K5/2274//4. Determining water use of indigenous grain and legume food crops. Pretoria, South Africa.

CHAPTER 11

ASSESSMENT OF SORGHUM–COWPEA INTERCROP SYSTEM UNDER WATER-LIMITED CONDITIONS USING A DECISION SUPPORT TOOL

Chimonyo, V.G.P., Modi, A.T. and Mabhaudhi, T.

11.1 Introduction

Despite moderate progress in yield improvements, crop productivity in rainfed rural agricultural systems remains low and cannot provide food security for current and future demands (Dile et al., 2013; Vanlauwe et al., 2014). Besides socio-economic and biophysical conditions, it has been observed that climate variability and change has resulted in a shift and change in duration of growing seasons, and increased incidences of seasonal dry spells and drought (Rosegrant et al., 2014). This has directly reduced agricultural water resources with an increase in water-scarce areas, and with formerly water-scarce regions becoming water stressed (Schilling et al., 2012). Given this scenario, farmers may not be equipped with the necessary risk management skills to adapt to the effects of climate variability and change (Venkateswarlu and Shanker, 2009). This is highlighted by continued water stress–related production losses. Researchers have, therefore, been tasked with coming up with relevant, innovative and practical adaptation strategies that are sustainable and resilient under water scarcity and stress.

There is renewed focus on restoration of sustainable and productive farming systems that are modelled on natural ecosystems (Mbow et al., 2014), and that can produce more from available water – 'more crop per drop' (Molden et al., 2010). As it stands, research has shown that intercropping has the potential to improve overall productivity through efficient and complementary use of water (Kour et al., 2013). The practice of intercropping is not new, but its advantages have not been fully exploited by rural farmers as a means to improve productivity, especially under water-limited conditions (Ouda et al., 2007). According to Chimonyo et al. (2015), this could be attributed to poor management options.

Decision-making is core in farm management and has been the focus of numerous studies dealing with risk aversion and adaptation in resource-limited rainfed farming systems (Jat and Satyanarayana, 2013; Lehmann et al., 2013; Mbow et al., 2014). According to Graeff et al. (2012), information to guide best management practices is widely available. However, the challenge for a farmer is to determine how to use the information with respect to the type of management decisions to be made and the current risk. Therefore, farmers need an efficient, relevant and accurate way to evaluate data for specific management decisions. To improve farmers' capacity to make the best management decisions, robust management tools such as crop simulation models (CSM) are now being employed to generate quick and relevant information to aid in decision-making.

Crop simulation models are computerised mathematical representations of crop growth, development and production, as a function of weather and soil conditions, and management practices that can reliably determine 'what if' and 'when' scenarios across diverse cropping system. Crop simulation models like APSIM (McCown et al., 1996) can assist in determining best management options at an operational and tactical level in response to low water availability. The objective of the study was, therefore, to apply a well-calibrated version of APSIM for a sorghum–cowpea intercrop to assess different management scenarios for selected areas in KwaZulu-Natal and thereby to define best management practices. Secondary to this, the model was used to identify best management practices to improve water use efficiency for sorghum–cowpea intercrop systems. The latter was achieved through scenario analyses based on a 10-year simulation period.

11.2 Material and Methods

11.2.1 Description of selected environments

KwaZulu-Natal, South Africa, has a diverse agro-ecological zone with 590 bio-resource units (BRUs) (Camp, 1999). Five sites located in five different BRUs in KwaZulu-Natal (Deepdale, Richards Bay, Umbumbulu, Ukulinga and Wartburg) were used in this analysis (Table 11.1). Richards Bay was considered as a low potential environment even though there is high annual rainfall (820–1 423 mm; Table 11.1). The location is characterised by sandy soils, which are generally considered as having low agricultural potential. Ukulinga and Deepdale were considered as moderate potential environments based on the annual rainfall received of 650–850 mm (Table 11.1). Umbumbulu and Wartburg were considered as high potential environments since they received high annual rainfall (800–1 200 mm) and have clayey soils. In contrast to sandy soils, clayey soils retain more water and nutrients (Table 11.1).

Table 11.1: Climate and soil description of sites to be included in the simulation.

	Deepdale*	**Richards Bay***	**Umbumbulu***	**Ukulinga****	**Wartburg****
Geographical location	28°01'S; 28°99'E	28°19'S; 32°06E	29°98'S; 30°70'E	29°37'S; 30°16'E	29.42° S; 30.57° E
Altitude (m a.s.l.)	998	30	632	775	880
Bio-resource unit	Coast hinterland thornveld	Moist coast forest, thorn and palmveld	Dry coast hinterland and ngongoni veld	Coast hinterland thornveld	Moist midlands mistbelt
Annual rainfall	750–850 mm	820–1 423 mm	800–1 160 mm	644–838 mm	900–1 200 mm
Average temperature	18.4°C	22°C	17.9°C	18.4°C	20°C
Frost occurrence	Moderate	None	Light and occasional	Moderate occasional	Light and occasional
Soil texture class	Clay	Sand	Clay	Clay	Clay loam
Clay content	53%	< 5%	> 60%	< 29%	< 33%
Soil type	Jonkersberg (Jb)	Inhoek (Ik)	Hutton (Hu)	Chromic luvisols	Chromic luvisols
Field capacity (%)	45.22	10.91	45.13	46.32	39.36
Permanent wilting point (%)	34.71	6.22	34.53	23.03	23.36
Saturation (%)	50.36	47.11	51.20	46.73	50.36

Adapted from *Motsa et al. (2015) and **Modi et al. (2014)

11.2.2 Model calibration and testing

The calibration and testing of the APSIM were carried out using data obtained from field experiments conducted during the 2013/14 and 2014/15 growing seasons of a sorghum–cowpea intercrop established at the University of KwaZulu-Natal's Ukulinga Research Farm. Sub-plots comprised intercrop combinations, that is, sole sorghum, sole cowpea and sorghum–cowpea. For details of field experimental output, refer to Chimonyo et al. (2016). During model testing, APSIM could simulate growth, yield, water use and water use efficiency of sorghum–cowpea across different water regimes. Slight differences were observed between observed and simulated results for sorghum–cowpea intercrop system for biomass accumulation (2.1%), water use (2.6%) and water use efficiency (4.6%).

11.2.3 Simulation

Simulations were performed using APSIM version 7.7. Details of model simulations are described below.

11.2.3.1 Climate

For each site, 10-year (2004–2013) weather data that contained daily estimates of rainfall, minimum and maximum temperatures, solar radiation and reference evapotranspiration were sourced from the SASRI weather site (SASRI, 2015) using the nearest station to the location, except for Ukulinga where there was a weather station on site (Table 11.1). Average ambient temperature (TAV) and the annual amplitude in monthly temperature (AMP) were calculated using long-term daily minimum and maximum temperatures. The calculated values of TAV and AMP were inserted in the met files by the software program named 'tav_amp'.

11.2.3.2 Soil

The soil modules in APSIM are based on the international and African classification format. The APSIM soil module required soil properties such as bulk density (BD), total porosity, saturation (SAT), drained upper limit (DUL), crop lower limit (LL), plant available water capacity (PAWC) and pH to simulate yields and soil water related processes.

For each agro-ecological zone, available soil information was matched to pre-existing soils in the APSIM soil module. Soils at Ukulinga were described as shallow clayey to clayey loam with medium fertility (Mabhaudhi et al., 2013), which was matched with Clay_Shallow_MF_101mm (Table 11. 2) in the APSIM soil file. Soils from Richards Bay were described as relatively deep and sandy with low fertility (Motsa et al., 2015), and were matched to Sandy_Medium_LF_111 mm (Table 11. 3) in the APSIM soil file. Soils in Umbumbulu and Deepdale were similar and were described as relatively deep and clayey with medium fertility (Motsa, 2015; Table 11.4), and were matched with Clay_Medium_MF_171 mm in the APSIM soil file. Soils in Wartburg were described as relatively deep and clay loam–loamy with medium fertility (Chibarabada, 2015; Table 11.5), and were matched with Loam_Medium_MF_125mm in the APSIM soil file.

Table 11.2: Properties of the African (generic) soil series available in APSIM's soil module, which best describe soil water properties in Ukulinga (the effective root zone for crops was considered to be 0–60 cm).

Depth	**Bulk density**	**Air dry**[1]	**LL15**[2]	**DUL**[3]	**SAT**[4]
(cm)	(g·cm^{-3})	(mm·mm^{-1})			
0–10	1.200	0.210	0.210	0.390	0.440
10–30	1.200	0.230	0.230	0.410	0.467
30–60	1.200	0.260	0.260	0.415	0.467

[1]Air dry – hygroscopic soil water content
[2]Crop lower limit (LL15) – Permanent wilting point (PWP); lower limit of the available soil water range and a point when plants have removed all the available water from a given soil, wilt and will not recover
[3]Drained upper limit (DUL) – field capacity (FC); amount of water remaining in a soil after the soil has been saturated and allowed to drain for approx. 24 h
[4]Saturation (SAT) – all pores in a soil are filled with water

Table 11.3: Properties of the African (generic) soil series available in APSIM's soil module, which best describe soil water properties in Richards Bay (the effective root zone for crops was considered to be 0–120 cm).

Depth	Bulk density	Air dry[1]	LL15[2]	DUL[3]	SAT[4]
(cm)	($g \cdot cm^{-3}$)	($mm \cdot mm^{-1}$)			
0–10	1.600	0.060	0.060	0.165	0.360
10–30	1.600	0.070	0.070	0.170	0.365
30–60	1.600	0.090	0.090	0.172	0.370
60–90	1.600	0.110	0.110	0.175	0.370
90–120	1.600	0.130	0.130	0.180	0.370

[1, 2, 3, 4] Refer to Table 11.2 footnote for descriptions

Table 11.4: Properties of the African (generic) soil series available in APSIM's soil module which best describe soil water properties in Umbumbulu and Deepdale (the effective root zone for crops was considered to be 0–120 cm).

Depth	Bulk density	Air dry[1]	LL15[2]	DUL[3]	SAT[4]
(cm)	($g \cdot cm^{-3}$)	($mm \cdot mm^{-1}$)			
0–10	1.200	0.210	0.210	0.390	0.440
10–30	1.200	0.230	0.230	0.410	0.467
30–60	1.200	0.260	0.260	0.415	0.467
60–90	1.200	0.290	0.290	0.420	0.470
90–120	1.200	0.320	0.320	0.425	0.475

[1, 2, 3, 4] Refer to Table 11.2 footnote for descriptions

Table 11.5: Properties of the African (generic) soil series available in APSIM's soil module, which best describe soil water properties in Wartburg (the effective root zone for crops was considered to be 0–120 cm).

Depth (cm)	**Bulk density** ($g \cdot cm^{-3}$)	**Air dry**[1]	**LL15**[2]	**DUL**[3]	**SAT**[4]
			($mm \cdot mm^{-1}$)		
0–10	1.400	0.170	0.170	0.301	0.400
10–30	1.400	0.180	0.180	0.310	0.410
30–60	1.400	0.190	0.190	0.310	0.420
60–90	1.400	0.215	0.215	0.315	0.430
90–120	1.400	0.250	0.250	0.317	0.440

[1, 2, 3, 4] Refer to Table 11.2 footnote for description.

11.2.4 Scenario analyses

Four management options were used to develop scenarios used as a guide for recommending best management practices in KwaZulu-Natal. The scenarios were:

11.2.4.1 Scenario 1: Planting dates

Three approaches (trigger season climate method, modelling and fixed date approaches) were used to establish the planting dates. The trigger season method is used to determine the onset and length of a growing season from long-term weather data and thus can be used to determine planting dates (Hartkamp et al., 2001). For this method, the onset of the season is assumed to be when the ratio of sum of monthly rainfall and reference evapotranspiration (ET_o) becomes greater than 0.5.

$$\frac{\text{Rainfall}}{\text{Reference evapotranspiration}} \geq 0.5 \qquad \text{Equation 11.1}$$

By plotting long-term monthly averages of rainfall, ET_o and 0.5 ET_o, the onset of a growing season can be determined by observing where rainfall exceeds 0.5 ET_o.

$$\text{Rainfall } \geq 0.5 \text{ reference evapotranspiration} \qquad \text{Equation 11.2}$$

An advantage to this approach is that it is site specific if weather data are available. On the other hand, a major limitation towards practical application of this method would be that farmers and extension service providers might not always have access to long-term weather data, specifically ET_o, from weather stations. For this exercise, planting dates, as defined by the onset of the growing season, were established based on 10-year monthly averages of rainfall, ET_o and 0.5 ET_o. For Ukulinga, Deepdale and Richards' Bay, trigger season occurred on 1 October while it occurred on 1 and 15 September for Umbumbulu and Wartburg, respectively (Fig 11.1).

The current planting dates in use by farmers are those recommended by agricultural agencies and extension service providers (Van Averbeke, 2002). These tend to be broad and do not accommodate large variation in agro-ecologies and their constantly shifting boundaries within sub-Saharan Africa. As it is, South Africa exhibits a wide variation of BRUs. Due to climate variability and change this variation has increased and there is an observed increase in land under semi-arid and arid regions since 2000 (Cairns et al., 2013). There was need to redefine planting dates, in terms of fixed dates, as this approach is much easier for farmers to work with. Five planting dates, 15 September, 15 October, 15 November, 15 December and 15 January were then used for the simulation representing early to late planting.

As a management tool, most CSMs can generate planting dates from climate and soil data. This is done based on predefined criteria that consider amount of rainfall, days taken to achieve that quantity, and soil water content within the seedling zone. The main advantage of using CSMs is that they are fast and reliable. They can also be site-specific, thus improving the accuracy of recommendations, or scaled up to give general assessment on a regional scale. For each site, APSIM was used to generate planting dates using a user-defined criterion of 'sum of rainfall in a 10-day period where at least a cumulative amount of 20 mm is received' (Raes et al., 2004). In addition, a fixed soil water content of 80% of field capacity of the top 15 cm was considered. The criteria set reflected planting conditions often used by farmers in semi-arid regions where planting is often done after the onset of the rainy season. Across the years, frequencies of planting dates falling in similar months were observed and mean planting date for that month was calculated. For evaluating crop yield and WUE, planting dates with the highest frequency of appearance within the 10-year weather data set were used for scenario analysis (Table 11.6).

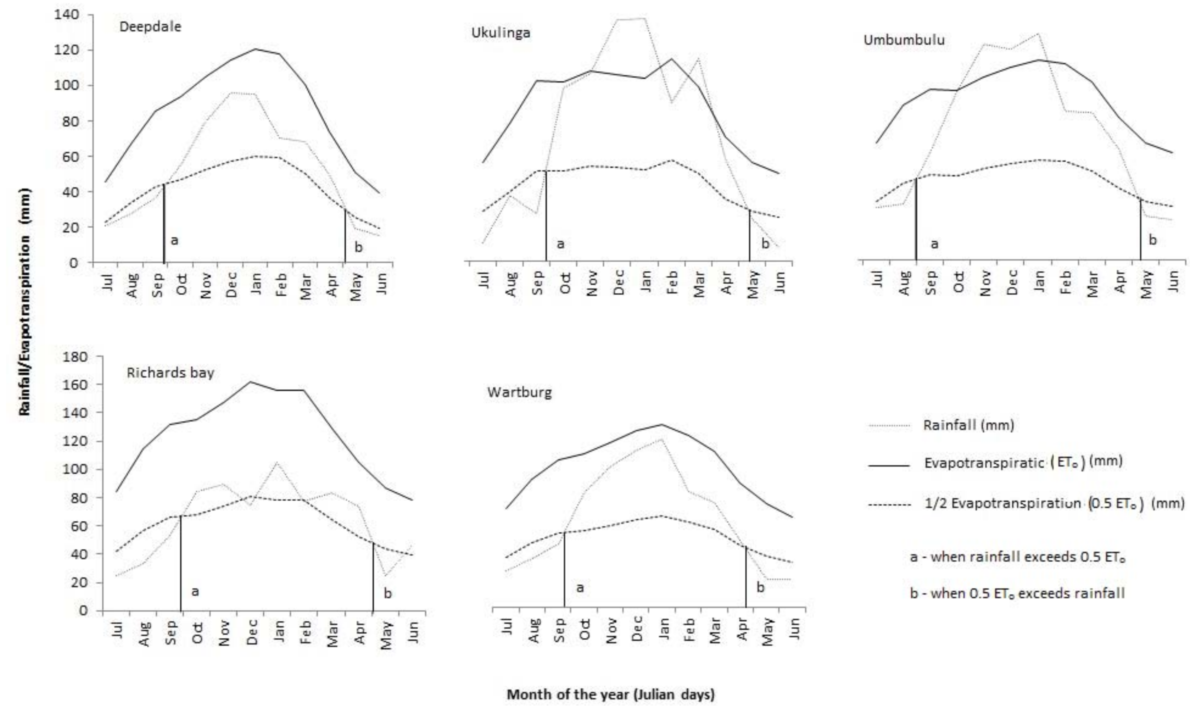

Figure 11.1: Determination of start and end of growing season for Deepdale, Richards Bay, Umbumbulu, Ukulinga and Wartburg using monthly average data over 10 years (2004–2013) for rainfall, reference evapotranspiration (ET_o) and 0.5 ET_o. The onset of a growing season (*a*) is when rainfall exceeds 0.5 ET_o. The period between *a* and *b*, is the length of the growing season. The end of the growing season (*b*) is marked by the decline of the rainfall to values below 0.5 ET_o.

Table 11.6: Model generated planting dates for the agro-ecological zones (Wartburg, Deepdale, Richards Bay, Umbumbulu, and Ukulinga) used in this study.

Site	**Mean planting date (Julian day)**	**Frequency (out of 10 years)**	**Standard deviation (+/-)[1]**
Wartburg	21 January	10	8.12
Umbumbulu	16 January	7	7.00
Ukulinga	15 January	6	7.18
Richards Bay	18 November	10	5.7
Deepdale	21 November	6	5.1

[1]Standard deviation (days) of mean planting date generated by the model

11.2.4.2 Scenario 2: Fertilizer application rates and time of application

Sorghum requires about 85 kg·ha^{-1} N to achieve a tonnage of 2 – 3.5 t·ha^{-1} (Wylie, 2004). Sorghum grain yields in SSA are approx. 900 kg·ha^{-1} on average, compared to the world average of 1 500 kg·ha^{-1} (Olembo et al., 2010). Increasing the yield to meet and/or surpass world averages would be desirable to improve access and availability of food. However, a major limiting factor is fertilizer use and accurate recommendations (Bationo, 2007). Based on recommendations by Wylie (2004), fertilizer levels representative of 0, 50 and 100% of the recommended N for optimum sorghum production were used for model scenario analyses. The range provided a scenario whereby farmers do not have access to fertilizers (0%), have some fertilizer (50%) or have 100% of the recommended N requirements.

11.2.4.3 Scenario 3: Plant populations

To determine the optimum plant population for the component crops for each site, simulations were performed using plant populations that were 50% less and 50% more than the recommended plant population. Under semi-arid conditions, a plant population of 26 666 plants·ha^{-1} is recommended for sorghum (du Plessis, 2008). For cowpea, an optimum plant population of 13 000 plants·ha^{-1} was used. These have been observed to give the best productivity in terms of land equivalent ratio of intercrop systems (Oseni, 2010). Simulations were carried out by maintaining the recommended plant population of one component and changing the other resulting in a total number of 10 simulations:

- Sorghum with a fixed population of 26 000 plants·ha^{-1} intercropped with cowpea with populations of 6 500 (A1), and 19 500 (A2) plants·ha^{-1}
- Sorghum with varying populations of 13 000 (B1), and 39 000 (B2) plants·ha^{-1} intercropped with cowpea with a fixed population of 13 000 plants·ha^{-1}
- The baseline population (C1) used to compare changes in yield and WUE was a sorghum and cowpea plant population of 26 000 and 13 000 plants·ha^{-1}, respectively.

11.2.4.4 Scenario 4: Irrigation

To reduce the yield gap that often occurs in rainfed farming systems due to water stress, supplementary irrigation was included as a management option. Two approaches were used, namely, deficit irrigation and rainfall-based approaches. Deficit irrigation (DI) is a method whereby irrigation is applied below full crop water requirement in such a way that there is little yield reduction and water is saved (Upchurch et al., 2005). Types of DI include (i) withholding irrigation until a predefined allowable soil water depletion of plant available water (PAW) before refilling the soil back to a predefined PAW, (ii) PAW is maintained at a predetermined level below full crop water requirement, and (iii) irrigation is only applied at full crop water requirements at critical growth stages (Fereres and Soriano, 2006). For this scenario, the first method for DI was used and allowable soil water depletion of 40% of PAW was defined before irrigation refilled it back to 80% of PAW. This ensured that soil water content never reached levels that could cause water or aeration stress to the plant.

In semi-arid conditions, rainfall distribution is an important factor affecting crop productivity. To manage this, supplementary irrigation during periods of low or no rainfall can reduce crop water stress and improve productivity. Irrigation scheduling was based on weekly rainfall where the conditions were that if rainfall received over 7 days was less than recorded ET_o for the same period, the difference would be applied as supplementary irrigation. This ensured that crop water requirement was met and that the crop did not suffer from water stress.

11.2.5 Data analyses and evaluation

Within the model, WU was determined as the sum of crop water uptake from the whole profile (sorghum Ep + cowpea Ep) and soil evaporation (Es). Each scenario was run independently from the other to minimise interactive effects of the scenarios. Since APSIM does not calculate WUE directly, simulated outputs (WU, yield and biomass) were used to determine WUE as follows:

$$\text{WUE}y = \frac{Y}{\text{WU}} \qquad \text{Equation 11.4}$$

where: WUE*y* = water use efficiency ($kg \cdot mm^{-1} \cdot ha^{-1}$), *Y* = total grain yield (sorghum + cowpea) ($kg \cdot ha^{-1}$), and WU = the crop water use (WU) (mm).

Descriptive statistics such as means, standard deviations, and box-and-whisker plots were used to analyse outputs. Box-and-whisker plots can show stability and general distribution of the sets of data.

11.3 Results and Discussion

11.3.1 Scenario 1: Planting dates

Different scenarios for planting dates gave different mean yields and mean yield distribution for sorghum and cowpea across the five environments over the simulated years. Based on the observed results, simulated average yields for sorghum at Richards Bay, Umbumbulu, Deepdale, Wartburg and Ukulinga were 952.7 (±185.42), 987.5 (±149.37), 820.5 (±122.99), 879.6 (±231.97) and 935.8 kg·ha^{-1} (±122.19), respectively. Yield averages for cowpea were 281.0 (±86.39), 355.9 (±153.24), 139.6 (±55.69), 260.1 (±153.36) and 321.7 kg·ha^{-1} (±110.58), respectively. Low yields observed for Deepdale for both sorghum and cowpeas could be due to the overall low rainfall at this site, while high yields observed for Umbumbulu, Richards Bay and Ukulinga were attributed to high rainfall received at these sites. Observed yields of sorghum were consistent with regional yield averages of 900 kg·ha^{-1} (Olembo et al., 2010). On the other hand, yields of cowpea were lower than those found by Ajeigbe et al. (2010) and Oseni (2010) who obtained yields between 400 and 900 kg·ha^{-1} under sorghum–cowpea intercropping. It should be noted that the differences in cowpea yield could be attributed to plant populations that were higher relative to current simulation studies. This would suggest that yields of cowpea within the intercrop system are influenced by population density.

The ideal planting date is a where overall yield are high and there is less variation over time (Kucharik, 2008). The ideal planting date for sorghum and cowpea at Richards Bay was that which was generated by the model (18 November) and this yielded an average of 1 050.7 kg·ha^{-1} (±45.57) for sorghum and 355.6 kg·ha^{-1} (±50.57) for cowpea. Similarly, the model generated planting date for Deepdale (21 November) and Ukulinga (15 January) simulated high yields for both sorghum (959.8±88.81 kg·ha^{-1} and 995.9±87.81 kg·ha^{-1}, respectively) and cowpea (160.6±38.57 kg·ha^{-1} and 156.5±42.63 kg·ha^{-1}, respectively) (Fig 11.2). For Umbumbulu, and Wartburg planting dates that gave high and stable yields for sorghum (970.8±106.32 kg·ha^{-1} and 1 037.2±68.78 kg·ha^{-1}, respectively) were observed by using a fixed planting date (15 October). The fixed planting dates did not always give high yields for cowpea, but results show yield stability as indicated by low standard deviations relative to other planting dates (426.2±134.94 kg·ha^{-1}, 332.8(±115.08 kg·ha^{-1}, 347.4±97.76 kg·ha^{-1}, respectively).

Sandy soils at Richards Bay are characterized as having low water-holding capacity due to large pore spaces between soil particles, such that water easily succumbs to drainage. Sandy soils require frequent wetting intervals to maintain desired soil water content (SWC) for seed germination, especially at the root zone. On the other hand, clayey soils like those at Deepdale require high amounts of rainfall to make water available for plants. Therefore, low rainfall during the early months of the official growing season may not be adequate for desired SWC at planting.

For low potential environments like Richards bay and Deepdale, using model-generated planting dates can avoid false starts to planting that is, planting dates that do not have all the requirements for ideal planting conditions. Fixed planting dates for Umbumbulu, Ukulinga and Wartburg were within the official planting window (15 Oct–15 Dec) for sorghum across the KwaZulu-Natal region (ARC, 2010). During this period, rainfall amount was observed to be high with an average of 95 mm·month^{-1} and evenly distributed. SWC is sufficient for seed germination and thereafter to sustain growth of developing seedlings.

In low rainfall areas (Deepdale and Wartburg), an early planting date (15 September) improved WUE (8.29% and 14.52%, respectively) for the intercrop system relative to planting dates that produced high yield. Under low-rainfall conditions it could be that, temporal use of radiation by the cropping system was increased resulting in an increase in biomass production and yield. Conversely, in high-rainfall areas (Ukulinga, Richards Bay and Umbumbulu), late planting dates (15 January) resulted in improvements of WUE (19.11%, 15.15% and 10.82%, respectively) relative to planting dates where high yields were observed. Improvements in WUE in high-rainfall environments was associated with low water use while yield remained unchanged (Table 11.7). Based on the model output, less water was lost through unproductive means (soil evaporation, runoff and drainage) relative to planting dates where high yields were observed. Although late planting was observed to improve WUE based on rainfall received during the growth period, including the whole season's rainfall in the calculation substantially reduced WUE. To increase temporal use of water, double cropping with early maturing cultivars of sorghum and cowpea can be employed. In the context of the sorghum–cowpea intercrop system, double cropping would be growing the cropping system twice in the same season in a relay manner.

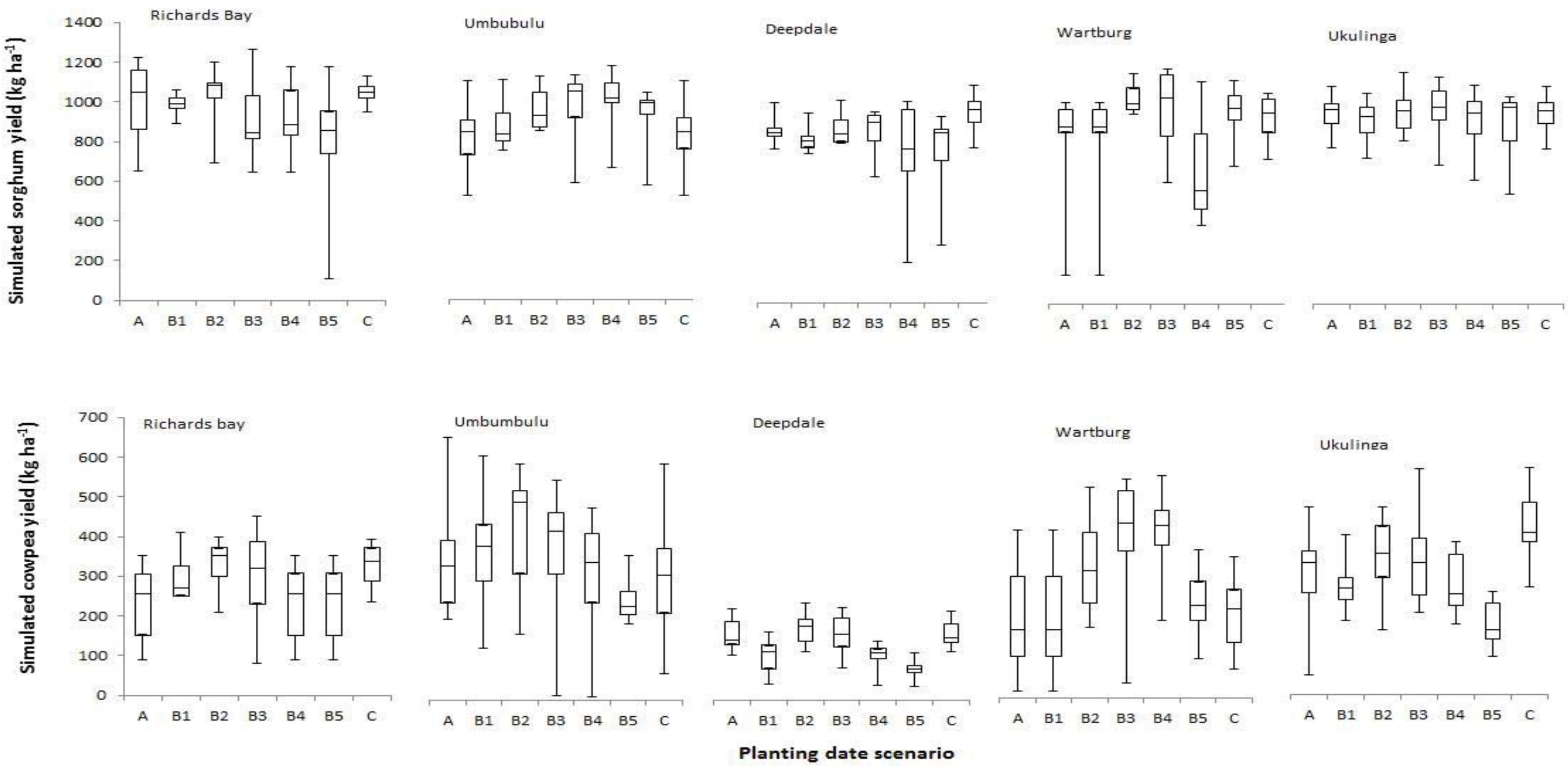

Figure 11.2: Simulated yield response of sorghum–cowpea intercrop system across the five environments (Richards Bay, Umbumbulu, Deepdale, Wartburg and Ukulinga) for different planting date scenarios. A: site-specific planting date defined by trigger season method. B1–5: fixed planting dates starting from (B1) 15 Sept, (B2) 15 Oct, (B3) 15 Nov, (B4) 15 Dec, (B5) 15 Jan, respectively. C: planting dates generated by APSIM.

Table 11.7: Comparison of simulated sorghum and cowpea yield, water losses, total water used (WU) and water use efficiency (WUE) in response to different environments and planting dates.

Environment	Planting date	Sorghum yield (kg·ha^{-1})	Cowpea yield (kg·ha^{-1})	Rainfall[1] (mm)	Water lost[2] (mm)	Cowpea water uptake[3] (mm)	Sorghum water uptake[4] (mm)	WU[5] (mm)	WUE[6] (kg·ha^{-1}·mm^{-1})	WUE impr[7] %
Richards Bay	15 Jan	983.6	296.4	278.22	232.66	31.97	27.15	291.79	4.42	15.15
Umbumbulu	16 Jan	951.1	251.7	314.14	286.26	33.98	21.68	343.11	3.56	10.82
Deepdale	15 Sep	811.5	104.0	246.57	199.47	23.15	32.08	254.71	3.86	8.29
Wartburg	15 Sep	928.2	249.9	259.91	229.15	38.44	25.03	322.62	3.91	14.52
Ukulinga	15 Jan	904.7	196.0	309.17	276.57	29.84	23.58	330.00	3.51	19.11

[1]10-year average rainfall received during the growing period
[2]Water lost through unproductive ways such as runoff, drainage and soil evaporation
[3]Water taken up and transpired by cowpea
[4]Water taken up and transpired by sorghum
[5]Amount of water used through productive (crop water uptake) and unproductive means (runoff, drainage and soil evaporation)
[6]Ratio of yield (kg·ha^{-1}) or crop output per water used to produce the yield
[7]WUE improvements relative to WUE obtained from ideal planting dates (21 Nov, 18 Nov, 15 Oct, 15 Oct and 15 Nov for Richards Bay, Umbumbulu, Deepdale, Wartburg and Ukulinga, respectively)

11.3.2 Scenario 2: Fertilizer application rate

Long-term simulation showed that overall yields were improved with the use of fertilizer (Table 11.8). The observed results were attributed more to an increase in sorghum yields than cowpea yields. Overall, adding 85 kg·ha^{-1} N had a more positive effect (12.7%) on sorghum yield than when 42.5 kg·ha^{-1} N was applied (5.7%). Results of simulations show that sorghum yields at Wartburg, Umbumbulu and Ukulinga were more responsive to fertilizer application (Table 11.8) when compared to Richards Bay and Deepdale. This was attributed to high rainfall amounts received at Wartburg, Umbumbulu and Ukulinga. The observed low responses to fertilization at Richards Bay and Deepdale were because plants absorb less nitrogen when soil water content is low. Adding high levels of fertilizer at Deepdale without improving water availability would not necessarily improve yields but rather could reduce the system's N use efficiency. On the other hand, the low improvements in sorghum yield in Richards Bay could be attributed to leaching during rainfall events. Richards Bay is characterised by sandy soils, which are generally associated with leaching. To improve fertilizer response of sorghum in environments with sandy soils, split applications and timing of application to coincide with specific growth stages should be considered.

Overall, adding 85 kg·ha^{-1} N had a more positive (5.08%) effect on WUE for the intercrop system than when 42.5 kg·ha^{-1} N was applied (3.43%). Improvements in WUE could have been attributed to increase in yield in response to fertilizer application. Improving soil fertility improves water use by increasing photosynthetic capacity of the leaf through improved enzyme function and enhanced carbon dioxide assimilation (Deng et al., 2006). Observed results for the interaction between WUE and N fertilizer agree with results by Gan et al. (2010), who observed an improvement in WUE with additions of different rates of N fertilizer. Under rainfed cropping systems application of fertilizer should always be considered as it has been observed to improve WUE.

Table 11.8: Simulation of yield, water use and water use efficiency and percentage improvements for yield and water use efficiency of sorghum-cowpea intercrop system in response to fertilizer.

Fertilizer	Environ.	Sorghum	Cowpea	Water use	WUE[1]	Yield impr[2].	WUE impr[3].
		(kg·ha^{-1})		mm	(kg·ha^{-1}·mm^{-1})	(%)	
42.5 kg·ha^{-1} N	Umbumbulu	1 002.3	296.9	301.79	4.64	5.12	5.14
	Ukulinga	915.4	197.5	363.11	3.06	4.56	0.62
	Richards Bay	952.5	232.6	259.71	4.63	5.13	4.92
	Deepdale	923.5	104.3	312.86	3.28	2.97	2.33
	Wartburg	1 023.9	249.4	331.90	3.96	7.91	3.73
85 kg·ha^{-1} N	Umbumbulu	1 060.3	295.3	306.79	4.69	12.51	6.97
	Ukulinga	988.7	196.8	360.11	3.29	15.65	2.74
	Richards Bay	1 006.7	295.4	253.71	4.71	7.63	3.52
	Deepdale	992.4	103.2	312.86	3.50	3.23	4.26
	Wartburg	1 126.82	238.96	321.76	4.24	23.12	7.91

[1]Water use efficiency
[2]Yield improvements relative to calculated yield simulated under 0 kg·ha^{-1} N
[3]WUE improvements relative to calculated WUE simulated from simulated crop water use (crop water uptake unproductive, water loss due to soil evaporation, drainage and runoff) under 0 kg·ha^{-1} N

11.3.3 Scenario 3: Plant populations

Results of plant population scenarios showed that different plant combinations resulted in different crop yield responses for both sorghum and cowpea. In general, changing the plant population of cowpea did not have a pronounced effect on sorghum (952.63±125.36 kg·ha^{-1}). It could be that cowpea did not compete with sorghum for resources such as radiation and water, and would suggest that the plant population of cowpea can still be increased further. Conversely, cowpea yield was affected by the change in sorghum population (Fig 11.3). For all the environments, reducing sorghum plant population improved cowpea yield by between 5.6 and 35.1%. Although increasing sorghum population increased its overall yield, results showed that this had a negative effect on simulated cowpea yield (12.63–16.38% reduction, Table 11.9). Sorghum was a stronger competitor for resources (radiation and water) than cowpea. Increasing the sorghum population might have increased the extinction coefficient of the top layer canopy and reduced the amount of solar radiation received by cowpea, the understorey. To improve yield of cowpea under high sorghum population, changing row orientations and arrangements can reduce competition for resources between sorghum and cowpea.

Under the B2 scenario (sorghum and cowpea plant populations of 39 000 and 13 000 plants·ha^{-1}, respectively), WUE was improved by an overall 10.39% relative to the baseline plant population. Improvements of WUE could be related to an increase in sorghum yield due to increased plant population. It was also observed that WU in Richards Bay (263.23±6.36 mm), Umbumbulu (336.56±8.51 mm), Deepdale (363.23±5.51 mm), Wartburg (353.23±4.61 mm), and Ukulinga (314.53±8.36 mm) was relative to corresponding WU of baseline populations across the sites (260.32, 339.25, 359.26, 352.30 and 310.25 mm). Increased yield output and unchanged WU thus resulted in an increase in WUE. Increasing plant population increases canopy size per unit area. This in turn increases water uptake and loss through transpiration, relative to that which would have been lost through soil evaporation. Under water scarcity, sorghum populations can be increased above the baseline population used in this study. However, this would not improve nutritional water productivity of the system. Maintaining sorghum populations and increasing cowpea populations could improve nutritional water productivity of sorghum–cowpea intercrop systems.

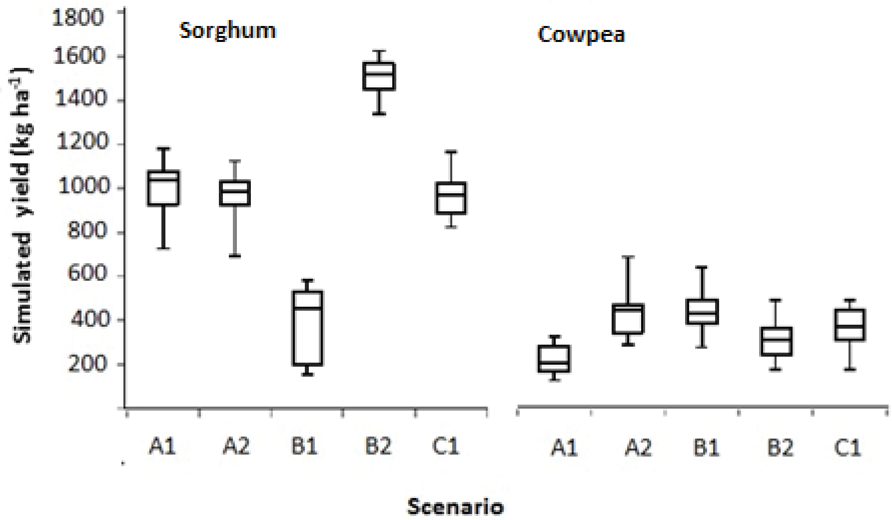

Figure 11.3: Simulated mean yield response of sorghum–cowpea intercrop system across the five environments (Richards Bay, Umbumbulu, Deepdale, Wartburg and Ukulinga) in response to different plant populations (A1 – sorghum 26 000 plants·ha^{-1} and cowpea 6 500 plants·ha^{-1}; A2 – sorghum 26 000 plants·ha^{-1} and cowpea 19 500 plants·ha^{-1}; B1 – sorghum 13 000 plants·ha^{-1} and cowpea 13 000 plants·ha^{-1}; B2 – sorghum 26 000 plants·ha^{-1} and cowpea 19 500 plants·ha^{-1} and C1 – sorghum 39 000 plants·ha^{-1} and cowpea 13 000 plants·ha^{-1}).

Table 11.9: Comparison of simulated sorghum and cowpea yield, water losses, total water used (WU) and water use efficiency (WUE) in response to different environments and plant populations.

Environ.	**Cowpea yield** (kg·ha^{-1})	**Sorghum yield**	**Average rainfall**	**Water lost**[1]	**Cowpea water uptake**[2] (mm)	**Sorghum water uptake**[3]	**WU**[4]	**WUE**[5] (kg·ha^{-1}·mm^{-1})	**WUE impr.**[6] (%)
Richards Bay	228.1	1 271.0	302.00	260.40	39.96	39.96	340.32	4.79	7.84
Umbumbulu	318.4	1 390.9	456.97	391.02	45.89	33.55	470.47	3.75	3.10
Deepdale	144.5	1 203.2	284.14	225.88	34.52	49.49	309.89	4.45	13.29
Wartburg	375.3	1 323.2	569.95	475.31	64.83	39.01	579.15	3.41	4.68
Ukulinga	1 453.8	360.3	421.03	322.92	37.83	37.83	404.78	4.61	23.81

[1]Water lost through unproductive ways such as runoff, drainage and soil evaporation
[2]Water taken up and transpired by cowpea
[3]Water taken up and transpired by sorghum
[4]Amount of water used through productive (crop water uptake) and unproductive means (runoff, drainage and soil evaporation)
[5]Ratio of yield (kg·ha^{-1}) or crop output per water used to produce the yield
[6]WUE improvements observed WUE relative to WUE obtained from baseline plant populations of 26 000 and 13 000 plants·ha^{-1} for sorghum and cowpea, respectively.

11.3.4 Scenario 4: Irrigation

Irrigation improved productivity and WUE of the sorghum–cowpea intercrop system (Table 11.10). Irrigating at weekly intervals based on rainfall analysis simulated higher yields (5.63%) relative to irrigation scheduling based on allowable soil water depletion (ASWD) across all the environments (Table 11.10). This could be because irrigation based on weekly rainfall events increased availability of water, reducing crops exposure to intermittent water stress. Across all environments, it was observed that irrigation had a large and positive effect on yield for both cowpea and sorghum at Richards Bay while the least effects were observed at Wartburg. Soils for Wartburg are clay-loam and, according to Kirkham (2005), clay-loam soils are good for irrigation since the clay component ensures good water-holding properties and the loam component good aeration and drainage. In contrast, soils at Richards Bay are deep and sandy and these soils are inherently well drained and well aerated, and have poor water-holding capacity. This often translates to significant drainage losses as opposed to the water being taken up by the plant. Conversely, the simulation results showed that water lost through unproductive means, namely drainage, was low. This could have been because rainfall was low but evenly distributed during the growth period. This meant that soil water was more available within the root zone and less was lost through unproductive means (Table 11.10). Scheduling irrigation based on weekly rainfall events can result in wasteful use of water by over-application of water relative to crop water requirements. This was quite evident with high amounts of water lost through unproductive means (Table 11.10).

Overall irrigation reduced WUE of the intercrop system relative to rainfed conditions. This could be attributed to high amounts of water lost through unproductive means under irrigation relative to rainfed conditions. This confirms early observations where, although yield improved, high amounts of water were lost through unproductive use. Conversely, results of WUE show that irrigating based on ASWD resulted in high (18.88%) WUE of the intercrop system relative to WIR. Similarly, the observed results could be attributed to large amount of applied water being lost through unproductive use. In this regard, ASWD can be suitable to improve yield of the intercrop system. However, to further increase WUE more irrigation water management options are required.

Table 11.10: Comparison of simulated sorghum and cowpea yield, water losses, total water used and water use efficiency in response to different irrigation scenarios and environments

Irrigation scheduling	Environment	Cowpea yield	Sorghum yield	Average rainfall	Water lost[1]	Cowpea water uptake[2]	Sorghum water uptake[3]	Irrigation	Total water added	WU[4]	WUE[5]
		(kg·ha^{-1})		(mm)							(kg·ha^{-1}·mm^{-1})
Soil water deficit	Umbumbulu	296.3	926.5	298.90	276.16	48.24	25.70	33.60	332.50	383.70	3.18
	Ukulinga	384.0	996.6	456.97	392.79	54.32	23.79	7.27	464.25	478.17	2.88
	R. Bay[7]	429.7	1209.3	284.14	244.09	35.39	49.85	36.36	320.50	365.69	4.48
	Deepdale	142.8	896.7	567.34	499.90	74.78	26.35	26.04	593.37	627.07	1.65
	Wartburg	406.9	1000.0	360.10	330.39	68.34	26.18	50.00	410.10	474.91	2.96
Rainfall	Umbumbulu	315.8	972.8	298.90	332.97	51.35	26.31	109.09	407.99	519.72	2.48
	Ukulinga	384.3	996.7	456.97	428.84	54.40	23.72	45.45	502.43	552.41	2.50
	R. Bay	429.3	1346.7	284.14	316.30	33.94	53.61	95.45	379.59	499.31	3.55
	Deepdale	143.7	935.6	567.34	673.60	74.72	27.09	200.97	768.31	976.38	1.10
	Wartburg	395.9	1009.3	360.10	371.23	64.94	26.39	64.00	424.10	526.56	2.66

[1]Water lost through unproductive ways such as runoff, drainage and soil evaporation
[2]Water taken up and transpired by cowpea
[3]Water taken up and transpired by sorghum
[4]Amount of water used through productive (crop water uptake) and unproductive means (runoff, drainage and soil evaporation)
[5]Ratio of yield (kg·ha^{-1}) or crop output per water used to produce the yield

11.4 Recommendations for Best Management Practices

Based on model scenario analyses, the following recommendations could be made for sorghum–cowpea intercrop system.

- To achieve high and sustainable yields, low potential environments similar to Deepdale and Wartburg (low annual rainfall) and Richards Bay (deep sandy soils) should plant intercrop of sorghum–cowpea around 15 November.
- Environments that receive high rainfall and are characterised by shallow clay soils like Ukulinga need to plant sorghum–cowpea intercrop system around 15 December. High rainfall areas with deep clay soils similar to Umbumbulu and Wartburg should plant on 15 October.
- To achieve high WUE, early planting (15 September) and late planting (15 January) in low-rainfall and high-rainfall areas, respectively, is recommended.
- Farmers in environments similar to Deepdale are advised to add 42.5 $kg{\cdot}ha^{-1}$ N since adding high quantities fertilizer will not always improve yield and WUE.
- Fertilizer levels of 85 $kg{\cdot}ha^{-1}$ N are recommended for use in high-rainfall environments such as Ukulinga, Richards Bay and Wartburg.
- Across all the environments, and where increasing sorghum yield and overall WUE is most desired, the ideal plant population of sorghum should be 39 000 $plants{\cdot}ha^{-1}$ in combination with 13 000 $plants{\cdot}ha^{-1}$ of cowpea.
- When yields of both crop species are desired increasing cowpea plant population to 19 500 $plants{\cdot}ha^{-1}$ is recommended.
- For all the environments, weekly scheduling of irrigation based on weekly rainfall amount resulted in high yields. However, this also produced low WUE. It can be recommended that, for all environments, using soil water deficit is better since yield and WUE were higher relative to weekly scheduling of irrigation based on weekly rainfall amount.
- To improve yields under irrigation, weather forecast data should be made readily available for farmers to improve irrigation management options and WUE.
- Using a 10-year data period for scenario analysis gave a good starting point for assessing the impacts of changes in management practices in an intercropping system. This is not, however, sufficient to reach strong and reliable conclusions (i.e., planting dates). Where

available, climate data for 30 years or more should be used to assess the effect of climate on intercrop management options.

- The determination/calculation of planting dates based on available data (historical and forecast data) should be recommended to resource-poor farmers, as it is affordable.

11.5 Conclusions

APSIM was efficient at assessing yield responses for sorghum–cowpea under different management scenarios for five rainfed agro-ecologies in KwaZulu-Natal. In addition, the model could identify best management practices for improved water use efficiency for sorghum–cowpea intercrops under rainfed conditions. For the environments included in this study, the sorghum–cowpea intercrop system was most responsive to changes in planting dates and plant populations while moderate changes were observed in response to fertilization and irrigation. Overall, the model can be used as a tool to develop best management options for increased yield and WUE for intercropping under water-scarce agro-ecologies. To improve the assessment of yield response for sorghum-cowpea intercrop to N fertilizer, site-specific N recommendations should be used in scenario analyses. There is still a need to apply APSIM to assess the effects of the combinations of these management options on yield and WUE for sorghum–cowpea intercrop systems.

References

Ajeigbe, H.A., Singh, B.B., Adeosun, J.O. and Ezeaku, I.E. 2010. Participatory on-farm evaluation of improved legume-cereals cropping systems for crop-livestock farmers: maize-double cowpea in Northern Guinea Savanna Zone of Nigeria. *Afr. J. Agric. Res.* **5** 2080–2088.

ARC (AGRICULTURAL RESEARCH COUNCIL, SOUTH AFRICA) 2010. Sorghum production guidelines. ARC Directorate Plant Production, Pretoria, South Africa.

Bationo, A., Waswa, B., Kihara, J. and Kim, Tu J. 2007. *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities*. Springer Science & Business Media. Springer, the Netherlands. http://dx.doi.org/10.1007/978-1-4020-5760-1

Cairns, J.E., Hellin, J., Sonder, K., Araus, J.L., Macrobert, J.F., Thierfelder, C. and Prasanna, B.M. 2013. Adapting maize production to climate change in sub-Saharan *Africa. Food Secur.* **5** 345–360. http://dx.doi.org/10.1007/s12571-013-0256-x

Chibarabada, T.P. 2014. Seed quality and water use characteristics of a Bambara groundnut (*Vigna subterranea* L) landrace differing in seed coat colour. MSc thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Chimonyo, V.G.P., Modi, A.T. and Mabhaudhi, T. 2015. Perspective on crop modelling in the management of intercropping systems. *Arch. Agron. Soil Sci.* **61** 1–19. http://dx.doi.org/10.1080/03650340.2015.1017816

Chimonyo, V.G.P., Modi, A.T. and Mabhaudhi, T. 2016. Water use and productivity of a sorghum–cowpea–bottle gourd intercrop system. *Agric. Water Manage.* **165** 82–96. http://dx.doi.org/10.1016/j.agwat.2015.11.014

Cooper, P.J.M., Dimes, J., Rao, K.P.C., Shapiro, B., Shiferaw, B. and Twomlow, S. 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agric. Ecosyst. Environ.* **126** 24–35. http://dx.doi.org/10.1016/j.agee.2008.01.007

Deng, X-P.X., Shan, L., Zhang, H. and Turner, N.C.N. 2006. Improving agricultural water use efficiency in arid and semiarid areas of China. *Agric. Water. Manage.* **80** 23–40. http://dx.doi.org/10.1016/j.agwat.2005.07.021

Dile, Y.T., Karlberg, L., Temesgen, M. and Rockström, J. 2013. The role of water harvesting to achieve sustainable agricultural intensification and resilience against water related shocks in sub-Saharan Africa. *Agric. Ecosyst. Environ*. **181** 69–79. http://dx.doi.org/10.1016/j.agee.2013.09.014

Fereres, E. and Soriano, M.A. 2006. Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.* **58** 147–159. http://dx.doi.org/10.1093/jxb/erl165

Flora, C.B. 2010. Food security in the context of energy and resource depletion: Sustainable agriculture in developing countries. *Renew. Agric. Food Syst*. **25** 118–128. http://dx.doi.org/10.1017/s1742170510000177

Gan, Y.T., Warkentin, T.D., Bing, D.J., Stevenson, F.C. and Mcdonald, C.L. 2010. Chickpea water use efficiency in relation to cropping system cultivar soil nitrogen and Rhizobial inoculation in semiarid environments. *Agric. Water Manage.* **97** 1375–1381. http://dx.doi.org/10.1016/j.agwat.2010.04.003

Graeff, S., Binder, J., Link, J. and Claupein, W. 2012. Crop models as decision support systems in crop production. INTECH Open Access Publisher. URL:

http://www.intechopen.com/books/crop-production-technologies/crop-models-as-decision-support-systems-in-crop-production (Accessed 5 October 2015).

Hartkamp, A.D., White, J.W., Rodríguez, A.M., Banziger, M., Srinivasan, G., Granados, G. and Crossa, J. 2001. Maize Production Environments Revisited: A GIS-based Approach. International Maize and Wheat Improvement Center (CIMMYT), Mexico.

Jat. M. and Satyanarayana, T. 2013. Fertiliser best management practices for maize systems. *Indian J. Fertil.* **9** 80–94.

Kirkham, M.B. 2005. *Principles of Soil and Plant Water Relations*. Elsevier, New York.

Kour, R., Sharma, B.C., Kumar, A., Aad Kour, P. 2013. Nutrient uptake by chickpea + mustard intercropping system as influenced by weed management. *Ind. J. Weed Sci.* **45** 183–188.

Kucharik, C.J. 2008. Contribution of planting date trends to increased maize yields in the central United States. *Agron. J.* **100** 328. http://dx.doi.org/10.2134/agrojnl2007.0145

Lehmann, N., Finger, R., Klein, T., Calanca, P. and Walter, A. 2013. Adapting crop management practices to climate change: Modeling optimal solutions at the field scale. *Agric. Syst.* **117** 55–65. http://dx.doi.org/10.1016/j.agsy.2012.12.011

Mabhaudhi, T., Modi, A.T. and Beletse, Y.G. 2013. Growth phenological and yield responses of a bambara groundnut (*Vigna subterranea* L Verdc) landrace to imposed water stress : II Rain shelter conditions. *Water SA* **39** 1–8. http://dx.doi.org/10.4314/wsa.v39i2.2

Modi, A.T., Mabhaudhi, T., Chimonyo, V.G.P., Hadebe, S.T., and Chibarabada, T.P. 2014. Determining water use of indigenous grain and legume food crops. Deliverable No.4 (unpublished), WRC Project No. K5/2274//4. Water Research Commission, Pretoria.

Mbow, M., Smith, P., Skole, D., Duguma, L. and Bustamante, M. 2014. Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Curr. Opin. Environ. Sustain.* **6** 8–14. http://dx.doi.org/10.1016/j.cosust.2013.09.002

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P. and Freebairn, D.M. 1996. APSIM: A novel software system for model development, model testing, and simulation in agricultural research. *Agric. Syst.* **50** 255-271. http://dx.doi.org/10.1016/0308-521x(94)00055-v

Misra, A.K. 2014. Climate change and challenges of water and food security. *Int. J. Sustain. Built Environ*. **3** 153–165. http://dx.doi.org/10.1016/j.ijsbe.2014.04.006

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A. and Kijne, J. 2010. Improving agricultural water productivity: Between optimism and caution. *Agric. Water Manage*. **97** 528–535. http://dx.doi.org/10.1016/j.agwat.2009.03.023

Motsa, N.M., Modi, A.T. and Mabhaudhi, T. 2015. Sweet potato response to low-input agriculture and varying environments of KwaZulu-Natal South Africa: implications for food security strategies. *Acta Agric. Scand. B Soil Plant Sci.* **65** 329–340. http://dx.doi.org/10.1080/09064710.2015.1011222

Nouri-Ganbalani, A., Nouri-Ganbalani, G. and Hassanpanah, D. 2009. Effects of drought stress condition on the yield and yield components of advanced wheat genotypes in Ardabil. *Iran. J. Food Agric. Environ*. **7** 228 – 234

Olembo, K.N., M'mboyi, F., Kiplagat, S. and Oyugi, F.K. (2010) *Sorghum Breeding in Sub-Saharan Africa.* African Biotechnology, Nairobi.

Oseni, T.O. 2010. Evaluation of sorghum-cowpea intercrop productivity in savanna agro-ecology using competition indices. *J. Agric. Sci.* **2** 229–234. http://dx.doi.org/10.5539/jas.v2n3p229

Ouda, S.A., El Mesiry, T., Abdallah, E.F. and Gaballah, M.S. 2007. Effect of water stress on the yield of soybean and maize grown under different intercropping patterns. *Aust. J. Basic Appl. Sci.* **1** 578–585.

Rosegrant, M.W., Koo, J., Cenacchi, N., Ringler, C., Robertson, R., Fisher, M., Cox, C., Garrett, K., Perez, N.D. and Sabbagh, P. 2014. *Food Security in a World of Natural Resource Scarcity Food security in a world of natural resource scarcity: The role of Agricultural Technologies.* International Food Policy Research Institute, Washington D.C.

SASRI (SOUTH AFRICAN SUGARCANE RESEARCH INSTITUTE). 2015. SASRI Weather Web. URL: http://sasex.sasa.org.za/irricane/tables/Ash_tables_AR.pl (Accessed 5 October 2015).

Schilling, J., Freier, K.P., Hertig, E. and Scheffran, J. 2012. Climate change vulnerability and adaptation in North Africa with focus on Morocco. *Agric. Ecosyst. Environ.* **156** 12–26. http://dx.doi.org/10.1016/j.agee.2012.04.021

Thrupp, L. 2013. Linking agricultural biodiversity and food security : the valuable role of agrobiodiversity for sustainable agriculture. *Int. Affairs* **76** 265–281.

Upchurch, D.R., Mahan, J.R., Wanjura, D.F. and Burke, J.J. 2005. Concepts in Deficit Irrigation: Defining a Basis for Effective Management. *Proc. World Water Environ. Resources Congr* Paper No. 9028. May 2005. American Society of Civil Engineers, Reston VA.

van Averbeke, W. 2002. Indigenous Technology and technology-oriented research : implications for research methodology. *Proc. 18th Annual Conference AIAEE 2002*, 26–30 May 2002, Durban. 451–457.

Vanlauwe, B., Wendt, J., Giller, K.E., Corbeels, M., Gerard, B. and Nolte, C. 2014. A fourth principle is required to define Conservation Agriculture in sub-Saharan Africa: The appropriate use of fertilizer to enhance crop productivity. *Field Crop Res.* **155** 10–13. http://dx.doi.org/10.1016/j.fcr.2013.10.002

Venkateswarlu, B. and Shanker, A. 2009. Climate change and agriculture: adaptation and mitigation stategies. *Indian J. Agron*. **54** 226–230.

Wang, J., Li, X., Lu, L. and Fa, N.G.F. 2013. Parameter sensitivity analysis of crop growth models based on the extended Fourier Amplitude Sensitivity Test method. *Environ. Model. Softw.* **48** 171–182. http://dx.doi.org/10.1016/j.envsoft.2013.06.007

WRC (WATER RESEARCH COMMISSION) 2014. WRC Knowledge Review 2013/14. Water Research Commission, Pretoria.

Wylie, P. 2004. Managing sorghum for high yields. A blueprint for doubling sorghum production. Grains Development Research Council (GRDC), Kingston ACT.

CHAPTER 12

GENERAL CONCLUSIONS AND RECOMMENDATIONS

Modi, A.T. and Mabhaudhi, T.

12.1 General Discussion

The focus of this study was on cereal and grain legumes that are produced in South Africa. The study was conducted to produce ten chapters, including review of literature (two chapters) and eight chapters derived from original field and modelling experiments. The review of literature assisted in identifying the major conventional and indigenous species of these crops and how they can be classified for production under water-scarce conditions similar to those that prevail in large parts of South Africa and sub-Saharan Africa. It is evident from the existing studies that indigenous cereal and grain legumes are underutilised although they have a great potential to minimise the negative effects of climate change on food security. In this context, the study recommends identification of cereal and legume crop species that are suitable for semi-arid conditions where rainfed agriculture is prevalent. In addition, it is recommended that the socio-economic value of these crops should be determined and they should be promoted as part of the agricultural value chain.

The review of literature also allowed planning of crop combinations for semi-arid regions in the context of crop modelling. In this context, determination of the response of indigenous/traditional varieties to production under a wide range of environmental conditions, compared with conventional cultivars was undertaken. Initial studies were based on determination of general crop growth and development. It was found that under low soil water availability, indigenous/traditional varieties showed adaptation through canopy size, CCI, SC, and phenological plasticity. Lack of significant genotypic differences in yield and WUE of underutilised indigenous crops and conventional crops highlighted that underutilised indigenous crops were equally suitable for production under sub–optimal conditions. Studies using multiple rain-fed agro–ecologies of SSA are required to conclude on water use, yield and WUE. Long-term weather data and analysis of rainfall distribution in relation to crop water use requirements at different growth stages would be valuable for knowledge of how water availability affects yield and WUE in rainfed sorghum.

Due to feasibility constraints, the use of crop models to extrapolate water use and yield potential of underutilised indigenous crops under rainfed agriculture is imperative.

A study to compare yield, water use and water productivity of selected major and traditional grain legume species under different irrigation regimes in a semi-arid environment showed that irrigation regimes did not show any significant effect on yield, water use and water productivity. The major legumes outperformed bambara groundnut with respect to yield, harvest index and water productivity. The major legumes used in the study were bred varieties while a landrace of bambara groundnut was used. This could be the reason for the inferiority of bambara groundnut. It highlights the need for crop improvement and breeding for yield in traditional grain legumes. The yield, water use and water productivity differences among the grain legume crops emphasizes the importance of growing appropriate crops to improve productivity under rainfed systems. However, decisions should not only be based on yield and water productivity of crops but should also consider the nutritional aspects to address the double burden of hunger and malnutrition.

Intercropping sorghum with cowpea and bottle gourd did not have any negative effect on growth and yield of sorghum. Under limited water availability, intercropping sorghum with either cowpea or bottle gourd resulted in more of a facilitative than competitive interaction with respect to water availability from a physiological, growth and productivity perspectives. Cowpea and bottle gourd could improve soil water availability by minimizing soil evaporation. In addition, cowpea could improve nutrient availability for sorghum and hence improve root function. This allowed for enhanced soil water capture from the soil profile and hence effective use of water. Physiological parameters (g_s and CCI) proved to be useful indices for evaluating sorghum response to intercropping under limited water availability. However, g_s was only evaluated in one season, hence further research is necessary to substantiate its usefulness. Under RF conditions, intercropping improved overall productivity of sorghum. Intercropping sorghum with cowpea resulted in improvement in WU. Overall, productivity (LER), WU and WUE (biomass and yield) for sorghum-cowpea intercrop system were more stable across both growing seasons. Results for sorghum-cowpea intercrop productivity still need to be substantiated since these are primarily based on the first season's data only. Under low water availability, intercropping should be recommended as a viable water management strategy. Sorghum–cowpea intercrop system should be recommended to semi–arid regions as it showed both yield stability and high WUE. There is a need for future research on the root-shoot responses of intercropped sorghum to varying levels of water availability, focusing more on root interactions. Intercropping maize with either dry bean or bambara groundnuts did not have any negative effect on growth and productivity of maize landrace. Under limited water availability, intercropping maize with either dry bean or bambara groundnuts resulted in more of a facilitative than competitive interaction with respect to water availability from a physiological, growth and productivity perspectives. Dry bean or bambara groundnuts could improve soil water availability by minimizing soil evaporation since they acted as live mulch. Overall, productivity for maize intercrop systems were more stable across both water regimes. However, under low water availability, maize – bambara groundnut resulted higher improvements in WUE and should be recommended as a viable water management strategy. However, productivity and WUE for the intercrop systems still need to be substantiated since these are primarily based on the first season's data only.

The AquaCrop model could simulate canopy cover, biomass accumulation, harvest index and yield relatively well for all sorghum genotypes and planting dates. The model did not accurately capture sorghum canopy decline, as it did not consider sorghum's quiescence growth habit, which allows for delayed canopy senescence under water–limited conditions. Conservative parameters in the default sorghum crop may not necessarily represent those of local genotypes, and this potentially contributes to overestimation of biomass and yield in the model. Despite minimum data input calibration simulating canopy cover relatively well, overestimation of biomass and yield suggests that conservative parameters such as water productivity (WP), canopy sensitivity to water stress, and water stress coefficient additionally require calibration for local genotypes to improve calibration. Where water conservation and crop growth characteristics are of primary importance, the use of minimum data input calibrated files is recommended due to very good simulations of crop canopy and phenological development. In cases where biomass and yield simulation are important, the use of the default file is recommended to reduce overestimation error. The results of this study suggest that where local sorghum genotypes differ significantly in growth and development characteristics from the default file, the use of minimal data input calibration potentially compromises prediction of crop yield. In terms of model application where extensive data is absent, it is recommended that users add parameters (WP), canopy sensitivity to water stress, and water stress coefficient) suggested in this study to improve calibration. For new sorghum cultivars that differ significantly in growth and development characteristics from the default crop file, it may be necessary to do a full calibration where possible to achieve good overall predictions of crop response to water availability.

The APSIM model could simulate sorghum–cowpea intercrop system under different water regimes. The model gave reliable simulations of phenology, biomass, yield and crop water use for both sorghum and cowpea under the different water regimes. Local adaptation of phenology and RUE coefficients proved to be useful in improving model simulations under the different water regimes. Simulations of biomass, yield and WU for sorghum–cowpea under rainfed conditions were overestimated and this resulted in a reduction of calculated WUEb. APSIM was limited in its ability to simulate under rainfed conditions. The model should use a dual approach of both RUE and transpiration efficiency to calculate biomass to improve simulations under water scarce areas. The model gave poor simulations of canopy development parameters leaf number and LAI. Improvements in model performance can be enhanced if it is able to capture extreme weather events. This will increase its applicability as a tool in risk management. APSIM can be used to come up with viable irrigation management strategies for sorghum-cowpea intercrop systems.

12.2 Conclusions

Indigenous grain and legume food crops are currently underutilised in South Africa relative to the major grain and legume crops. This is despite the fact that most indigenous grain and legume food crops possess attributes that make them ideal for rainfed agriculture, especially under semi-arid and arid conditions. The study showed that crops such as sorghum, bambara groundnut and cowpea have low levels of water use compared to major crops. In addition, they are often drought and heat stress tolerant and adapted to low input agriculture systems which typify the semi-arid and arid cropping systems. Whilst not the focus of this study, the initial reviews of literature also showed that indigenous grain and legume food crops were often nutrient dense and thus suited to addressing the water-food-nutrition-health nexus in poor rural area. The use of crop models showed that while research on these crops is still lagging, crop models can be used to hasten the divide and aid in developing best practice management recommendations. The use of best management practices that include intercropping, appropriate cultivar and planting date selection as well as rainwater harvesting and conservation techniques have potential to improve current yields and improve water productivity under rainfed conditions.

12.3 Recommendations

The major recommendations derived from this study are:

1. Indigenous and traditional varieties of cereal and legume grain crops should be promoted as part of agriculture. Their potential role in crop production under challenging climate change conditions and their potential in addressing food insecurity in semi-arid regions has been shown in literature and in this study.
2. Although these crop varieties have less yield potential compared to improved conventional crop varieties, management practices that include intercropping, appropriate choice of site and planting date have shown that these crops can play a significant role in the "more crop per drop" strategy in agriculture.
3. The two models, AQUACROP and APSIM are useful in determining the physiological and yield parameters of indigenous and traditional cereal and legume crops under different management practices to allow scheduling of planting dates under a wide range of environments.

12.4 Future Direction

This study was useful in providing some basic empirical information on indigenous grain and legume crops. However, as both literature reviews pointed out, there are still challenges to realising the potential of these crops to meaningfully contribute to food security:

- There is need to commission a short-term study that can review existing policies and initiatives in South Africa to set-out how indigenous crops can be mainstreamed into existing agricultural programmes that are aimed at smallholder farmers. This could also focus on empowering women and youths and getting them to participate in the new value chains;
- There is need to target a few indigenous food crops that have the most potential for success and conducting research across the entire value chain, up to product development;
- The use of crop modelling has potential to bridge the knowledge gap between underutilised and major crops. This can significantly reduce the time and costs associated with conducting traditional experiments to generate new information. However, most major crop models have not been calibrated and validated for the vast range of indigenous crops. Conducting studies on calibrating and validating crop models for selected underutilised

crops could be useful, this could then support the development of value chains for those specific underutilised crops.

- While this study focussed on food security, several underutilised grain and legume crops could also be considered for biofuel production as alternative biofuel feedstock. Since most already have low water use and are suited to marginal production areas, this would also align with the Biofuels Regulatory Framework's aims of not increasing agricultural water use from biofuel feedstock production. Again, this would be opening new value chains for these crops which would stimulate their uptake and production.

APPENDIX I: CAPACITY DEVELOPMENT REPORT

Project No: **K5/2274//4**
Project Title: **DETERMINING WATER USE OF INDIGENOUS GRAIN AND LEGUME FOOD CROPS**
Project Leader: **PROF. ALBERT T. MODI**
Organisation: **UNIVERSITY OF KWAZULU-NATAL**

STUDENT NAME AND SURNAME	GENDER	RACE	DEGREE	UNIVERSITY	COUNTRY OF ORIGIN	STATUS
VIMBAYI CHIMONYO	FEMALE	AFRICAN	PHD	UKZN	ZIMBABWE	COMPLETED
SANDILE HADEBE	MALE	AFRICAN	PHD	UKZN	SOUTH AFRICA	COMPLETED
NOKHUTHULA HLANGA	FEMALE	AFRICAN	MSC	UKZN	SOUTH AFRICA	COMPLETED
TENDAI CHIBARABADA	FEMALE	AFRICAN	MSC	UKZN	ZIMBABWE	COMPLETED
ILUNGA KALANDA	MALE	AFRICAN	MSC	UKZN	D.R. CONGO	COMPLETED
THOBEKA MANYATHI	FEMALE	AFRICAN	MSC	UKZN	SOUTH AFRICA	COMPLETED
FARAI MAZVIMBAKUPA	FEMALE	AFRICAN	MSC	UKZN	ZIMBABWE	COMPLETED
WINILE SHELEMBE	FEMALE	AFRICAN	MSC	UKZN	SOUTH AFRICA	COMPLETED
VELELO XONGWANA	MALE	AFRICAN	MSC	UKZN	SOUTH AFRICA	COMPLETED

QUANTIFYING PRODUCTIVITY AND WATER USE OF SORGHUM INTERCROP SYSTEMS

Vimbayi Grace Petrova Chimonyo

ABSTRACT

Rural sub-Saharan Africa (SSA) faces the challenge of achieving food security under water scarcity amplified by climate variability and change. Under these conditions, it is necessary to adopt cropping systems that have potential to improve productivity. The aim of the study was to assess the feasibility of a sorghum-cowpea-bottle gourd intercrop system with a view to determine the resource use efficiencies. This was achieved through a series of studies, which included critical literature reviews, quantifying water use and water use efficiency of sorghum-cowpea-bottle gourd, and modelling using Agricultural Production Systems Simulator (APSIM). Field trials were conducted at the University of KwaZulu–Natal's Ukulinga Research Farm over two seasons (2013/14 and 2014/15) under varying water regimes [full irrigation (FI), deficit irrigation (DI) and rainfed (RF)]. Intercrop combinations considered were sole sorghum, cowpea and bottle gourd as well as intercrops of sorghum–cowpea and sorghum–bottle gourd. Data collected included soil water content, plant height/vine length, leaf number, tillering/branching, leaf area index, relative leaf water content, stomatal conductance and chlorophyll content index as well as biomass accumulation and partitioning. Yield and yield components, water use (WU) and water use efficiency (WUE) were calculated at harvest. Extinction coefficient, intercepted photosynthetic active radiation (IPAR) and radiation use efficiency (RUE) for biomass and grain were also determined. Land equivalent ratio (LER) was used to evaluate intercrop productivity. Growth, yield and water use of the sorghum–cowpea intercrop system were simulated using APSIM. The validated model was then used to develop best management practices for intercropping. The review showed that aboveground interactions within intercrop systems have thoroughly been investigated while belowground interactions were mostly limited. The review highlighted the potential of bottle gourd as a versatile food crop. The field trials established that sorghum yields were stable across different water regimes. This was mainly achieved through facilitative interaction within the intercrop systems, which allowed for greater eco-physiological adaptation resulting in improved water capture and use. Improved water capture and use also increased WUE (50.68%) and RUE (8.96%). The APSIM model simulated growth, yield and WU of the intercrop system under varying water regimes satisfactorily. The model over–estimated biomass (6.25%), yield (14.93%) and WU (7.29%) and under–estimated WUE (-14.86%). Scenario analyses using APSIM showed that the development of best management practices should be agro–ecology specific to ensure dynamic climate change adaptation strategies and increase resilience. It was concluded that intercropping results in improved productivity, especially under water–limited conditions. As such, it that can be used by farmers located in semi-arid and arid regions as an adaptation strategy for increased productivity.

WATER USE OF SELECTED SORGHUM (*SORGHUM BICOLOR* L. MOENCH) GENOTYPES

Sandile Thamsanqa Hadebe

ABSTRACT

Water scarcity is a major limitation to crop production in sub–Saharan Africa (SSA). Under these conditions, determining and predicting crop yield response to water in rainfed agriculture is useful for improving water productivity and food security. This study aimed to determine water use characteristics and water use efficiency of different sorghum genotypes as well as to model water use of such sorghum genotypes for extrapolation to other rainfed agro–ecologies. A review of water use of major cereal crops was conducted to gain insight into strategies to improve water productivity under arid and semi–arid agro–ecologies. To quantify water use and determine water use efficiency (WUE) of sorghum under different environmental conditions three sorghum genotypes, namely, PAN8816 (hybrid), Macia (open–pollinated) and Ujiba (landrace) were planted at two sites (Ukulinga and Umbumbulu) under rainfed conditions in 2013/2014 and 2014/15 seasons. Furthermore, PAN8816, Macia, Ujiba and IsiZulu (landrace) genotypes were planted at Ukulinga under early, optimal and late planting dates to determine sorghum water use characteristics (morphological, physiological, phonological and yield). Field trials planted at Ukulinga in 2013/14 were used to calibrate the AquaCrop model for PAN8816, Macia and Ujiba. Model testing was conducted using observations from three planting dates at Ukulinga during the 2014/15 season. Thereafter, PAN8816 and Ujiba crop files were used to apply AquaCrop to extrapolate to other rainfed agro–ecologies in South Africa (Deepdale, Richard's Bay and Ukulinga) and develop best management recommendations for rainfed sorghum production. During the 2013/14 season, WUE was significantly lower at Umbumbulu (7.49 kg mm^{-1} ha^{-1}) relative to Ukulinga (11.01 kg mm^{-1} ha^{-1}). This was attributed to low total available water at Umbumbulu. Macia had higher WUE (10.51 kg mm^{-1} ha^{-1}) relative to PAN8816 (9.34 kg mm^{-1} ha^{-1}) and Ujiba (7.90 kg mm^{-1} ha^{-1}); however, differences were not significant. During the 2014/15 season, sorghum genotypes adapted to low water availability through reduced canopy size and duration, low chlorophyll content index and stomatal conductance, as well as hastening phenological development. The AquaCrop model satisfactorily predicted yield response to water for the studied sorghum genotypes during calibration and testing. When applied for scenario analysis, the model performed well for the range of agro–ecologies considered. This study confirmed drought tolerance and high WUE of sorghum and it is concluded that sorghum is uniquely suitable and adapted to production under semi– and arid agroecologies of SSA. Furthermore, the study confirmed the use of the AquaCrop model as a simple, relatively accurate tool to predict sorghum yield response to water.

SEED QUALITY AND WATER USE CHARACTERISTICS OF A BAMBARA GROUNDNUT (*VIGNA SUBTERRANEA* L.) LANDRACE DIFFERING IN SEED COAT COLOUR

Tendai Polite Chibarabada

ABSTRACT

Bambara groundnut (*Vigna subterranea* L.) is an underutilised African legume that fits the same ecological niche as *Arachis hypogea* (groundnuts). Because of its reported drought tolerance and high water use efficiency there are now renewed efforts to study bambara groundnut with a view to promoting it as an alternative crop in marginal production areas. It is still cultivated using unimproved landraces, and little is known about their seed quality. There is need for information describing aspects of their seed quality in order for farmers to successfully produce the crop. The study evaluated seed quality and seedling water use characteristics of selected seed coat colours of bambara groundnut. Lastly, the study investigated the effect of water stress imposed on maternal plants on subsequent yield and seed quality of bambara groundnut. A single bambara groundnut landrace was characterised into four distinct selections based on seed coat and speckling colour; plain red, plain cream, cream with brown speckles (brown speckled) and cream with black speckles (black speckled). Seed quality (viability and vigour) was evaluated using the standard germination, electrolyte conductivity and imbibition tests as well as water activity, seed coat thickness and mineralogy. Seedling water use characteristics were evaluated under varying water regimes (25%, 50% and 75% field capacity). Measurements included plant growth and physiological (chlorophyll content index and chlorophyll fluorescence) responses up to 21 days after planting; thereafter seedling water use efficiency was determined. Irrigation was withdrawn thereafter in all water treatments to determine physiological and metabolic responses (total soluble sugars, antioxidants and phenols) to terminal stress. A field trial was grown in 2013/14 summer season under irrigated and rainfed conditions. Yield and yield components as well as subsequent seed quality (viability and vigour) of progeny was determined from harvested material. Darker coloured seeds and seeds with similarly coloured speckles showed better viability while the plain cream landrace selection was more vigorous. Seedling water use efficiency in bambara groundnut improved with decreasing water availability. Drought avoidance strategies and acclimation to water stress were also found to be present at the seedling establishment stage. Yield was negatively affected by water stress. Subsequent seed viability and vigour were respectively higher in seeds produced under irrigated and rainfed conditions. The study concluded that although bambara groundnut is a water use efficient crop, water stress may affect yield and subsequent seed quality.

WATER USE CHARACTERISTICS OF SELECTED SOUTH AFRICAN MAIZE (*ZEA MAYS* L.) LANDRACES COMPARED WITH COMMERCIAL HYBRIDS

Farai Mazvimbakupa

ABSTRACT

In South Africa, maize is the staple food, especially in rural areas. The majority of people in these areas rely on rainfed farming for their agricultural production. Traditional maize landraces are still a feature of the agricultural landscape in rural areas thereby indicating their importance. However, climate change poses a threat to the availability of water, particularly in sub-Saharan Africa where drought is deemed prevalent. The aim of the study was, therefore, to compare the water use characteristics of two maize landrace varieties, GQ1 and GQ2 (originating from Gqunge location, Centane Eastern Cape, South Africa) with two popular high yielding commercial hybrids (SC701 and PAN53). Initially, seed quality testing was determined using the standard germination, electrical conductivity and tetrazolium tests. A controlled environment study was then conducted in which the landraces were compared to hybrids across three water regimes [30% crop water requirement (ETc); 50% ETc and 80%ETc]. Separate field studies were conducted to evaluate the growth, development, yield and yield components of these varieties under varying environmental conditions – Ukulinga (irrigated and rainfed) and Swayimane (rainfed). Results of seed quality tests showed that landrace GQ2 had comparable seed quality to hybrids. However, overall, hybrids had superior seed quality to landraces. Results from the controlled experiment also showed that emergence of landrace GQ2 was at par with hybrids. Subjecting both landraces and hybrids to water stress (50% ETc and 30% ETc) resulted in shorter plants compared to non–stressed plants (80% ETc). Plants also tasselled earlier in response to water stress. The landrace GQ2 continued to perform similarly to hybrid varieties under water stress conditions. In field trials, the dominance of hybrids, attributed to hybrid vigour, was more pronounced under optimum conditions than sub-optimum conditions. Under a low input system (Swayimane), landraces performed at par with hybrids. It can therefore be concluded that landraces of good seed quality may be suitable for cultivation under sub-optimum low input systems where their ability to adapt enables them to produce stable yields and still provide a valuable germplasm resource.

PHYSIOLOGICAL RESPONSES OF COWPEA (*VIGNA UNGUICULATA*) TO WATER STRESS UNDER VARYING WATER REGIMES

Kalanda Ilunga

ABSTRACT

Water stress has been reported as one of the most important environmental factors affecting crop productivity in the world, particularly in semi– and arid regions. Climate change, through changes in rainfall amount and patterns, remains a serious threat to crop productivity in these regions that are already food insecure. There is a need to identify and promote more drought tolerant crops with low levels of water use for production in these areas. Cowpea [*Vigna unguiculata* (L) Walp.] has been reported to be more adapted to drought-prone conditions, compared to other crops. Its multi-purpose uses, high protein content and potential to biologically fix nitrogen makes it best suited for production by resource-poor farmers. However, cowpea has not been given the attention it deserves as a crop that has potential to contribute towards food security and improve diets of people living in marginal areas of agricultural production. This study evaluated cowpea physiological responses to water stress under controlled and field conditions. Two cowpea varieties (Brown mix and White birch) were evaluated for seed quality, on a comparative basis of seed coat colour, using standard germination and electrolyte conductivity tests, under laboratory conditions. A pot trial was conducted under controlled environmental conditions (33/27°C day/night; 65% RH) to evaluate cowpea responses to water stress under three water regimes (30% ETc, 60% ETc, and 80% ETc). Thereafter, field trials were conducted to determine the effect of planting date selection on cowpea productivity under irrigated and rainfed conditions. Results of seed quality showed that the Brown mix variety was more viable than White birch. However, results of vigour were contrary to results of viability and indicated that the White birch was more vigorous than the Brown mix. Under controlled environmental conditions, water stress had a negative effect on cowpea stomatal conductance, thereby limiting plant growth and productivity. Water stress had no effect on leaf chlorophyll content index. For all three planting dates, cowpea emergence was affected by temperature; the crop requires warm temperatures for successful stand establishment. Consequently, growth and physiology were also more affected by temperature than water availability. Cowpea performed better under rainfed than irrigated conditions and produced more yield. The Brown mix variety seemed to favour vegetative growth over reproductive growth and thus maybe suitable for production as a leafy vegetable. Overall, the White birch variety was more adapted to limited water availability than Brown mix.

WATER PRODUCTIVITY OF SELECTED SORGHUM VARIETIES

Thobeka Manyathi

ABSTRACT

The majority of people living in rural communities rely on rainfed farming for their agricultural production. Under these conditions, water stress through drought or uneven rainfall distribution is a major limitation to crop production. Sorghum is drought tolerant and has the ability to produce reasonable yields under water-limited conditions. The aim of this study was to evaluate crop growth and development under varying water regimes and determine water use of three sorghum varieties (PAN8816, Macia and Ujiba landrace). Two pot trial studies were conducted under controlled environment conditions. The first study evaluated the responses of three varieties (PAN8816, Macia and Ujiba) to water stress imposed at different growth stages [no stress (NS), vegetative stress (VS), reproductive stress (RS) and yield formation stress (YS)]. Thereafter, harvested seeds were subjected to seed quality tests. The second study determined the water productivity of three sorghum varieties (PAN8816, Macia and Ujiba). Results showed that the reproductive and yield formation stages were the most sensitive to stress. Sorghum demonstrated a degree of phenological plasticity in response to water stress imposed at different growth stages. Ujiba performed similar to the hybrid and open–pollinated varieties under all water regimes and better under water-limited conditions. Under optimum conditions, PAN8816 used water more productively compared to Ujiba and Macia. The high water productivity was associated with the high leaf area. Progeny from the NS and VS water regimes showed high germination capacity with the exception of progeny from plants subjected to water stress (RS and YS). It can be concluded that the Ujiba landrace may be recommended for cultivation by farmers in water-limited areas because of its ability to produce reasonable yields under water stress. Water stress during reproductive and yield formation stages results in yield losses and poor seed quality in subsequent seed.

EVALUATING THE RESPONSE OF THREE DRY BEAN (*PHASEOLUS VULGARIS* L.) CULTIVARS TO PLANTING DATE UNDER IRRIGATED AND RAINFED CONDITIONS

Velelo Xongwana

ABSTRACT

Planting date and water availability during crop growth affect quantity and quality of grain crops, including dry beans (*Phaseolus vulgaris* L.). The aim of the study was to determine the interactive effects of planting date and water availability on crop growth, yield and seed quality of three dry bean cultivars, Caledon, Gadra and Ukulinga. The cultivars differed with respect to growth habit. Caledon is a type II, indeterminate medium season crop. Gadra is a type I, determinate, short season cultivar. Ukulinga is a bush type, long season cultivar. The planting dates were designed to be two weeks apart so that the first planting date was on February 17 2014, the second and third planting dates were two and four weeks later, respectively. The crop was planted at the same plant population and fertilised similarly at planting. Two water availability treatments were irrigation and dry land (rainfed) production. Growth parameters that affect yield, namely, plant height, leaf number, leaf area index, and chlorophyll content index were determined at flowering. In addition, pod number per plant, seed number per plant and grain yield were determined. The experiment was arranged as a split-split-plot design, with planting date as the main plot, irrigation as sub-main plot and cultivar as sub-sub-plot to determine statistical differences between factors with respect to the measured variables. Results showed that there were significant differences between cultivars with respect to all variables, largely due to genotypic differences. Delaying the planting date by two and four weeks from 17 February at Ukulinga farm had a negative effect on key growth parameters such as plant height, leaf number, pod number per plant, and seed number per plant. Consequently, early planting improved yield by up to 40%. Irrigation improved grain yield by up to 50% across all cultivars and planting dates. It is recommended that dry beans should be planted early in the season, while the air and soil temperature are warm and to avoid drought and cooler temperatures that occur later in the season. Planting late in the season under unfavourable water availability conditions has a negative effect on growth parameters and subsequently grain yield.

INTERCROPPING MAIZE LANDRACES, BAMBARA GROUNDNUTS AND WILD MUSTARD: EFFECT ON SOIL FERTILITY AND PRODUCTIVITY

Winile Shelembe

ABSTRACT

South Africa is water scarce country and faces food insecurity at household level. Food production in South African smallholder farming is made difficult by other factors such as maintaining soil fertility. Most soils lack a wide range of nutrients, particularly nitrogen and phosphorus, and there is little likelihood of increasing production unless nutrient levels improve. Methods of improving food security have been implemented and have been found to be unsuccessful and farmers have relied on farming systems. The widely used cropping system by smallholder farmers is intercropping. Intercropping is the cultivation of two or more crops in the same space at the same time. This system may enable an intensification of the farm system, leading to increased productivity as compared to monocropping. At a local level, intercropping does contribute to food security and improved nutrition through dietary diversity. The aim of the study was to evaluate productivity of maize–bambara groundnut and maize–wild mustard intercrops. Secondary to this, the study aimed at determining the effect of these different intercrop combinations on soil fertility. The treatments were sole maize, bambara groundnut, wild mustard, maize-bambara groundnut intercropping and maize-wild mustard intercropping. The treatments were allocated into three blocks of different fertiliser levels (100%, 50% and 0%). Growth parameters (plant height, leaf area and number, and chlorophyll content), biomass, yield and yield components were determined. It was observed that intercropping reduced growth and yield, while fertiliser application resulted in their increase. It was observed that intercropping led to better use of soil water due to increased root density. Intercropping maize with bambara groundnut and wild mustard increased nitrogen and phosphorus, respectively. The effect of intercropping and fertiliser application on seed quality was also determined. The results showed that intercropping had no effect on viability of bambara groundnut progeny, while intercropping produced wild mustard progeny with low germinability. Application of fertiliser resulted in increased seed quality indices (germination and vigour). It can be concluded that it is advantageous to include a legume in an intercropping system especially for smallholder farmers who cannot afford to buy fertilisers. Intercropping is associated with greater productivity and savings in land, which could be used for other agricultural purposes. Intercropping maize with bambara groundnut and wild mustard improves soil nutrients, especially nitrogen and phosphorus.

APPENDIX II: REPORT ON RESEARCH DISSEMINATION

A. Published Articles

1. Hadebe, S.T., Modi, A.T. and Mabhaudhi, T. 2017. Calibration and testing of AquaCrop for selected sorghum genotypes. Water SA 43(2) (in press).

2. Hadebe, S.T., Modi, A.T. and Mabhaudhi, T. 2017. Water use of sorghum (*Sorghum bicolor* L. Moench) in response to varying planting dates. *Water SA* 43: 91-103.

3. Chibarabada, T.P., Modi, A.T. and Mabhaudhi, T. 2017. Expounding the value of grain legumes in the semi− and arid tropics. *Sustainability* 9, 60; doi:10.3390/su9010060.

4. Chimonyo, V.G.P., Modi A.T. and Mabhaudhi, T. 2016. Water use and productivity of a sorghum-cowpea-bottle gourd intercrop system. *Agricultural Water Management* 165, 82–96.

5. Chimonyo, V.G.P., Modi A.T. and Mabhaudhi, T. 2016. Simulating yield and water use of a sorghum–cowpea intercrop using APSIM. *Agricultural Water Management* 177, 317–328.

6. Chimonyo, V.G.P., Modi A.T. and Mabhaudhi, T. 2016. Assessment of sorghum–cowpea intercrop system under water-limited conditions using a decision support tool. *Water SA* 42, 316–327.

7. Hadebe, S.T., Modi, A.T. and Mabhaudhi, T. 2016. Drought tolerance and water use of cereal crops: a focus on sorghum as a food security crop in sub-Saharan Africa. Journal of Agronomy and Crop Science. doi:10.1111/jac.12191.

8. Chibarabada, T.P., Modi, A.T. and Mabhaudhi, T. 2015. Water use characteristics of a bambara groundnut (*Vigna subterranea*) landrace during seedling establishment. *Water South Africa* 41, 472–482.

9. Chivenge, P.P., Mabhaudhi, T., Modi, A.T. and Mafongoya, P. 2015. The potential role of neglected and underutilised crop species as future crops under water scarce conditions in sub-Saharan Africa. *International Journal of Environmental Research and Public Health* 12, 5685-5711.

10. Mazvimbakupa, F., Modi, A.T. and Mabhaudhi, T. 2015. Seed quality and water use characteristics of maize landraces compared with selected commercial hybrids. *Chilean Journal of Agricultural Research* 75, 13-20.

11. Chimonyo, V.G.P., Modi A.T. and Mabhaudhi, T. 2015. Perspectives on crop modelling in management of intercropping systems. *Archives of Agronomy and Soil Science,* 61, 1511–1529.

12. Chibarabada, T.P., Modi, A.T. and Mabhaudhi, T. 2015. Bambara groundnut (*Vigna subterranea*) seed quality in response to water stress on maternal plants. *Acta Scandinavica Section B: Plant & Soil Science,* 65, 364–373.

13. Chibarabada, T.P., Modi, A.T. and Mabhaudhi, T. 2014. Seed quality characteristics of a bambara groundnut (*Vigna subterranea* L.) landrace differing in seed coat colour. *South African Journal of Plant & Soil* 31, 219–226.

B. Manuscripts in Review

1. Chimonyo, V.G.P, Modi, A.T. and Mabhaudhi T. Sorghum radiation use efficiency and biomass partitioning in a sorghum-cowpea-bottle gourd intercrop system. *Field Crops Research* (Submitted on the 20th January 2017).
2. Hadebe, S.T., Modi, A.T. and Mabhaudhi, T. Nutritional water productivity of selected sorghum genotypes in response to planting date. *Journal of Cereal Science* (Submitted on the 14th of January).

C. Conference Proceedings

1. Chimonyo, V.G.P., Modi A.T. and Mabhaudhi, T. In press. Applying APSIM for evaluating intercropping under rainfed conditions: A preliminary assessment. In proceedings of the Fifth Conference on Climate and Development in Africa (CCDA-V), Victoria Falls, Zimbabwe. 28 – 30 October 2015.

D. Popular Articles

1. Mabhaudhi, T. and Modi, A.T. 2016. Sowing the seeds of knowledge on underutilised crops. *Water Wheel*, March/April 2016, pp 40-41.
2. Staff Reporter. 2016. UKZN forges ties with Biowatch and smallholder farmers. *Farmer's Weekly*, 18 March 2016, pp 27.

E. Theses

1. Hlanga, N.C. 2017. Planting date, water availability and plant population effects on dry bean production (*Phaseolus, vulgaris* L.). MSc Thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa.
2. Chimonyo, V.G.P. 2016. Quantifying productivity and water use of sorghum intercrop systems. PhD Thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa.
3. Hadebe, S.T. 2016. Water use of selected sorghum (S*orghum bicolor* L. Moench) genotypes. PhD Thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa.
4. Xongwana, V. 2015. Evaluating the response of three dry bean (*Phaseolus vulgaris* L.) cultivars to planting date under irrigated and rainfed conditions. MSc Thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa.
5. Shelembe, W. 2015. Intercropping maize landraces, bambara groundnuts and wild mustard: Effect on soil fertility and productivity. MSc Thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa.
6. Manyathi, T. 2015. Water productivity of selected sorghum varieties. MSc Thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa.
7. Mazvimbakupa, F. 2014. Water use characteristics of selected South African maize (*Zea mays* L.) landraces compared with commercial hybrids. MSc Thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa.
8. Ilunga, K. 2014. Physiological responses of cowpea (*Vigna unguiculata*) to water stress under varying water regimes. MSc Thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa.
9. Chibarabada, T.P. 2014. Seed quality and water use characteristics of a bambara groundnut (*Vigna subterranea* L.) landrace differing in seed coat colour. MSc Thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

F. List of Published Abstracts

1. Hadebe, S.T., Modi, A.T. and Mabhaudhi, T. "Calibration and testing of AquaCrop for selected sorghum genotypes." Combined Congress, Klein-Kariba, Bela Bela, Limpopo, South Africa, 23-26 January 2017.
2. Mabhaudhi, T. and Modi, A.T. "Including underutilised crops in the crop choice for irrigation and sustainable food production." South African National Commission on Irrigation and Drainage (SANCID) Symposium, Goudini Spa, 11 – 13 October 2016.
3. Chimonyo, V.G.P, Modi, A.T. and T Mabhaudhi. "Using APSIM to determine water use efficiency of a sorghum-cowpea-bottle gourd intercrop system." South African National Commission on Irrigation and Drainage (SANCID) Symposium, Goudini Spa, 11 – 13 October, 2016.
4. Modi A.T. and Mabhaudhi, T. "Sustainable agriculture" Ukulinga Howard Davis Memorial Symposium, Ukulinga Research Farm, UKZN, Pietermaritzburg, 24 – 25 May 2016.
5. Mabhaudhi, T. and Modi, A.T. "Fitting neglected and underutilised crops into climate change adaptation strategies." Adaptation Futures, Rothermstead, Netherlands, 10-15 May 2016.
6. Chimonyo, V.G.P, Modi, A.T. and T Mabhaudhi. "Sorghum–cowpea intercrop: yield and water simulation using APSIM model" Combined Congress of South Africa, Bloemfontein, South Africa, 18 – 22 January 2016.
7. Mabhaudhi T. and Modi A.T. "Drought tolerance of selected neglected and underutilised crops from South Africa." Combined Congress of South Africa, Bloemfontein, South Africa, 18 – 22 January 2016.
8. Hadebe, S.T., Modi, A.T. and Mabhaudhi, T. "Water use of sorghum (S*orghum bicolor* L. Moench) in response to varying planting dates" Combined Congress, Bloemfontein South Africa, 18-21 January 2016.
9. Chimonyo, V.G.P, Modi, A.T. and T Mabhaudhi. "Applying APSIM for evaluating intercropping under rainfed conditions: A preliminary assessment", Fifth Conference on Climate and Development in Africa (CCDA-V), Victoria Falls, Zimbabwe. 28–30 October 2015.
10. Mabhaudhi T. and Modi A.T. modelling crop water productivity. Southern African Regional Irrigation Workshop, Harare, Zimbabwe, 20-22 July 2015.

11. Chibarabada, T.P and Modi, A.T. "Water use characteristics of a bambara groundnut landrace during Seedling establishment." Annual College of Agriculture, Engineering and Science Post-graduate Research Day, University of KwaZulu-Natal Durban, 27 October 2014.

G. List of Poster Presentations

1. Chimonyo, V.G.P, Modi, A.T. and T Mabhaudhi. "Water use efficiency of maize intercrop systems." Combined Congress, Klein-Kariba, Bela Bela, Limpopo, South Africa, 23-26 January 2017.

2. Chibarabada, T.P and Modi, A.T. "Seed quality of a Bambara groundnut landrace (*Vigna subterranea*) differing in seed coat colour." Combined Congress, Rhodes University South Africa, 20-23 January 2014.

3. Chibarabada, T.P., Modi, A.T. and Mabhaudhi, T. "Effect of production water regime on bambara groundnut (*Vigna subterranea*) seed quality." Combined Congress, University of Free State South Africa, 19-21 January 2016.

4. Hlanga, N.C. and Modi, A.T. "Determining the seed quality of dry bean seed: certified versus first generation seed lot." Combined Congress, University of Free State South Africa, 19-21 January 2016.

9781431208876