QUANTIFYING PRODUCTIVITY AND WATER USE OF SORGHUM INTERCROP SYSTEMS

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DECLARATION

I, Vimbayi Grace Petrova Chimonyo, declare that

1. The research reported in this thesis, except where otherwise indicated, is original work and has not been submitted for any degree or examination at any other university.
2. This thesis does not contain data, pictures, graphs or other information from other researchers, unless specifically acknowledged as being sourced from other persons.
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DEDICATION

This work is dedicated to my father

GENERAL ABSTRACT

Rural sub-Saharan Africa (SSA) faces the challenge of achieving food security under water scarcity amplified by climate change and variability. Under these conditions, it is necessary to adopt cropping systems that have a potential to improve productivity. The aim of the study was to assess the feasibility of a sorghum-cowpea-bottle gourd intercrop systems with a view to determine the resource use efficiencies. This was achieved through a series of studies which included conducting critical literature reviews, quantifying water use and water use efficiency of sorghum-cowpea-bottle gourd, and modelling such systems 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 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 (ET) 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 showcased 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 was simulated growth, yield and WU of an 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. Dynamic agronomic management practices should be adapted to further increase the system's resilience to predicted climatic uncertainties. Future studies on intercropping should consider root interactions and possibly different plant populations and planting geometry as factors that might influence resource capture and use. Decision support systems should be promoted within farming communities to better manage risks associated with on-farm decision making

TABLE OF CONTENTS

CHAPTER 1

GENERAL INTRODUCTION AND OVERVIEW

Justification and objectives

Within sub-Saharan Africa, population is projected to increase from 1.1 billion to 2.4 billion by 2050 (Dile et al., 2013). To feed the rapidly growing population, food production will have to double from current levels (Misra, 2014). Conversely, the amount of water and land available for food production continues to decline owing to increased pressure from competing uses (Rosegrant et al., 2014). In addition, climate change and variability has increased the occurrence and severity of droughts, further constraining the availability of water for agriculture (Misra, 2014). As it is, South Africa is a semi-arid country whose water profile is rapidly moving from water scarce to water stressed (Singels et al., 2010). Rainfall is unevenly distributed, with about 50% of the rain falling on 15% of the land (Crétat et al., 2012). It is in most of the remaining 85% of the country where rural inhabitants are concentrated (Shackleton et al., 2008). They are characterised as practising rainfed agriculture and are generally food insecure (Beddington et al., 2011). Increasing agricultural activities within rural communities has been identified as a means to improve food security. However, due to the aforementioned water situation, productivity is low and will not be able to sustain projected population growth. In light of this, the use of drought tolerant crop species such as sorghum can result in the most productive use of the dwindling resource.

Sorghum 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). The crop can thrive in areas that receive as little as 500 mm rainfall during the growing season (Hadebe et al., n.d.). This is attributed to eco-physiological and eco-morphological traits that enable it to capture and use water efficiently. Although sorghum possesses several unique drought adaptation traits, literature indicates that yields observed throughout the region are far below world yield average of 2.5 t ha^{-1} (Sitii Aishah et al., 2011). This is still attributed to water stress associated with poor agronomic and water management strategies (Rockström et al., 2010). At a plant level, responses to water stress have been shown to be complex (Farooq et al., 2014), involving adaptive changes and/or deleterious effects. Likewise, mitigating water stress should be multifaceted and employ a combination of strategies (de Ponti et al., 2012).

1

By employing water management strategies such as intercropping, productivity of sorghum rainfed production systems of can be improved. This is can be achieved through efficient capture and use of water (Ogindo and Walker, 2003; Ouda et al., 2007; Singh and Behari, 2012; Jun et al., 2014). However, information on the mechanisms behind improved water use in intercropping is scanty.

Understanding water use of a crop is an effective decision making tool in areas prone to water stress (Kijima et al., 2011). This, coupled with water saving strategies, has seen an increase in crop production in water stressed regions of the world (Yuan et al., 2003). Water within the soil is lost primarily through evapotranspiration, deep percolation and runoff (Sadras et al., 2012). To minimise and redirect water lost through non-productive processes to plant use, traditional cropping systems such as intercropping have been observed to improve the availability of soil water. This is achieved through maximising root volume and depth, and increasing canopy cover; thus reducing soil evaporation (Carlson, 2008). With the observed reduction in arable land in South Africa, intercropping has been shown to increase production output per unit area. Intercropping sorghum (*Sorghum bicolor* (L.) Moench.) with either bottle gourd (*Lagenaria siceraria* (Molina) Standl.) or cowpea Cowpea (*Vigna unguiculata* L. Walp.) could increase water use within a given system through improved resource use efficiency (land, water and solar radiation), thus increasing yield and ultimately food production. The success of such a cropping system would depend, to a large extent, on the complementary use of growth resources such as water, solar radiation and nutrients, especially if water is in limited supply. Therefore, research has to be directed at assessing feasibility of a range of intercrop combination within the limitations of available resources.

Measuring productivity and use of water in mixed systems requires a careful balancing of possibilities and needs. As a way of generating information that can increase the accuracy of recommendations, Ogindo and Walker (2003) suggested the use of crop growth models that take into account inter- and intra-specific competition within the root and canopy system of an intercrop. According to Miglietta and Bindi (1993), crop modelling is the dynamic simulation of crop growth by numerical integration of constituent processes with the help of computers. Crop models have facilitated a quantitative understanding of the effects of crop growth and agronomic management factors on crop development and productivity (Chipanshi et al., 1999). Crop modelling offers a cost-effective and fast alternative to exploring cropping scenarios and estimating their productivity under a range of management and environmental conditions (Raes et al., 2009). The use of crop models in predicting water productivity and

2

crop performance within intercrops could assist in generating useful information for policy formulation, especially in environments where water is a scarce resource (Malézieux et al., 2009). With the adoption of crop simulation techniques presented in this study, there is a possibility for developing strategies for smallholder farmers that can reduce risks associated with monocropping and rainfall variability.

The effects of climate change and variability on water availability, and subsequently food security, are a reality. To improve rural food security, and ultimately livelihoods, cropping systems need to develop resilience to future climate uncertainties. Due to its drought tolerance, sorghum is ideal for semi–arid and arid agro–ecological regions. However, large yield gaps have been observed due to poor water management practices across farming systems within the semi–arid and arid regions. It can be hypothesised that, ecological type farming systems like intercropping can increase productivity of sorghum through enhanced water capture and utilisation. While several studies have quantified water use and water use efficiency of popular intercrop systems such as maize – bean (Miriti et al., 2012; Ogindo and Walker, 2005), there is a dearth in knowledge for sorghum intercrop systems especially using a modelling approach. Therefore, the aim of the study was to quantify water use and water use efficiency of sorghum intercrop systems using field and modelling approaches.

The specific objectives of the study were:

  i.   to conduct a critical review of available literature on quantifying and modelling resource use in intercrop systems,
  ii.   to conduct a critical review of available literature on agronomic potential of bottle gourd for use in water management strategies,
  iii. to quantify water and radiation use and determine the water and radiation use efficiency of sorghum-cowpea-bottle gourd intercrop systems, and
  iv.   to calibrate APSIM for sorghum–cowpea intercrop system and apply it in assessing different management scenarios for several rainfed agro-ecologies in KwaZulu–Natal climatic conditions for best management practices.

2.2 Thesis structure

To address the objectives of the study, agronomic and modelling experiments were conducted over two seasons (2013/14 and 2014/15). This thesis is written in paper format. Where manuscripts have already been published, it is stated so, and where such manuscripts have been submitted to journals and are under review, information is also provided stating the journal name and submission date. The thesis consists of seven interlinked chapters, excluding the present chapter.

Chapter 2 addresses the first objective through a literature review of issues pertaining to resource use, namely water and radiation, in intercrop systems. Crop simulation models (CSM) as decision support tools for intercrop/multicrop systems and future directions for modelling multicrop systems were also reviewed. It also justifies the use of APSIM as a tool to model resource use and productivity of intercrop systems.

Chapter 3 addresses the second objective and clarifies the inclusion of bottle gourd within this study. A review of bottle gourd as a food security crop and a crop to be included for use in water management strategies was conducted. Seed quality was identified as a major yield reducing factor. The latter part of the review uses empirical results to determine the relationship between agro-morphological characteristics and seed quality.

Chapter 4 addresses the third objective through field experiments conducted at Ukulinga Research Farm, Pietermaritzburg. The objective of field trials was to determine the eco-physiological and eco-morphological responses of sorghum when intercropped with either cowpea or bottle gourd under varying water regimes. Results of canopy (leaf area index, plant height and leaf number), physiological parameters (stomatal conductance, chlorophyll content index), yield and yield components are presented. In addition, results of land equivalent ratio (LER), water use and water use efficiency are also presented.

Chapter 5 is intrinsically linked with chapter four in the sense that the same field experiment and treatment structures were used. The major differences are the parameters reported. In this chapter the main focus is radiation interception and use efficiency of sorghum when intercropped with either cowpea or bottle gourd under varying water regimes. Specific leaf area, biomass partitioning and radiation interception, and radiation use efficiency, of sorghum are reported.

Chapter 6 reports on local adaptation and testing of APSIM model for sorghum–cowpea intercrop systems in response to different water regimes. It is related to the fourth objective of the study. To conduct a local adaptation of APSIM to simulate crop responses of sorghum–cowpea intercrop system, site specific soil and climate data and crop specific parameters (time to emergence, time interval between emergence and end of juvenile stage, time interval between end of juvenile stage and flowering, RUE) are used. Data were obtained from field trials conducted in the 2013/14 season. To test the model, data from 2014/15 season obtained from varying water regimes was used.

Chapter 7 is written as a sequel to Chapter 6 and uses the model APSIM to establish best management practices for improved water management. It also addresses the last objective of the study. Using the adapted and tested APSIM sorghum – cowpea model, the response of yield and WUE to agronomic practices planting dates, plant population, fertiliser application rates and irrigation scheduling were assessed for five agro-ecologies within the KwaZulu–Natal region. For each agronomic trait, best management practices were identified.

Chapter 8 is the general discussion, integrating the separate studies to address the main study aims and objectives. It highlights the major findings and implications and the conclusion to the thesis. Lastly, it also provides future direction.

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CHAPTER 2

MODELLING RESOURCE USE OF MULTICROP SYSTEMS: A REVIEW OF CONCEPTS AND SELECTED MODELS

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Abstract

The risk to food security is particularly dire in rural sub-Saharan Africa (SSA) where a third of the world's undernourished people reside. Intercropping has potential to improve rural livelihoods through better resource utilization and improved resilience to current and future challenges. This paper reviewed concepts in intercropping and outline how resources are captured and utilized within the system. Crop simulation models (CSM) as decision support tools for intercrop/multicrop systems and future directions for modelling multicrop systems are the focus of the review. Through increased crop biodiversity, intercropping improves resilience, food security and nutrition. This is achieved through improved resource capture and utilisation due to differences in spatial and temporal distribution of component crops. For farmers to maximise on these advantages, they need to have full knowledge of species combination, arrangements and proportions. A major drawback to intercrop systems is that most of the existing agronomic recommendations are tailored on monoculture practices. This is also evident in the structure of most CSMs that cannot account for heterogeneous crop stands. In conclusion, there is a need to enhance agricultural research on intercrop systems, combining conventional and modern research approaches. Moreover, CSMs should be multi-dimensional in order to simulate system diversity accurately.

Key words: crop simulation models, parameterization, resource use

Introduction

Food security exists when all people, at all times, have physical and economic access to and/or produce sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life (FAO 2013). While the risk to food security is a global one, the issue is particularly dire in rural Sub-Saharan Africa (SSA) where a third of the world's undernourished people are found (Garrity et al. 2012). According to the United Nations' 2014 technical report for post-2015 development agenda 'Solutions for sustainable agriculture and food systems', food insecurity is projected to increase as the region witnesses an increased rate of rural - urban migration, economic and political crises relapse and increased incidences of extreme weather conditions. As it stands, access to food by rural communities in the region remains largely from agriculture and is small-scale and subsistence-focused (FAO 2013). Although in isolation, this has promoted rural livelihoods

(Garrity et al. 2010), it remains inadequate for sustainable self-sufficiency at a national and regional level (FAO 2013). The region is thus faced with the task of improving current food security and at the same time coming up with strategies to ensure future food security in wake of worsening climate (Schmidhuber and Tubiello 2007). That being said the case, focus has intensified on safe guarding rural food security through improved agricultural innovations so that they can shift from being net food consumers to producers that can actually feed themselves and growing urban populations (Garrity et al. 2012).

Rural agriculture is characterized by multiple bio-physical and socio-economic constraints that have resulted in low productivity of existing systems (FAO 2013). Moreover, farming practices have been modelled around principles of intensive agriculture (Garrity et al. 2012). While such practices have brought about localized improved productivity, it is widely recognized that these activities are not sustainable for rainfed systems and are poor buffers towards extreme weather events and depleting soil fertility. To date, greater yield losses can be accounted for by drought than other crop production factors (Sheffield et al. 2014). This has resulted in reduction of agricultural activities across SSA and has reduced progress towards food security. In light of increasing incidences and severity of drought, growing population and food demand, it becomes imperative to remodel current marginalized farming systems so that they become resilient and sustainable for improved food security.

Owing to the shortcomings of pro-green revolution farming and increased demand for food, there has been a resurgence of interest in agricultural systems that are founded on the basis of sustainable agriculture through increased on-farm biodiversity (Garrity et al. 2010). Research has shown that an improvement in on-farm biodiversity, if assembled correctly in time and space, can lead to farming systems that can naturally buffer extreme weather events (Gurr et al. 2003), regulate resource use and competition and reduce risk of pests and diseases through biological or direct control; ultimately ensuring sustainable food security (Altieri 2002; Scherr and McNeely, 2008) and enhanced resilience. In selected regions of India, South America (Ebert 2014) and North Africa (Jalloh 2002), the increase in tree and crop biodiversity through intercropping has increased food security. China prides itself for increasing rural livelihoods through the reintroduction of biodiversity through intercropping and other traditional farming systems (Knorzer et al. 2009). This evidence suggests that intercropping could successfully improve farm-biodiversity in marginalized parts of sub-Saharan Africa.

By definition, intercropping is the growing of two or more crops together, in proximity, on the same piece of land during a growing season (Ranganathan 1992). The practice is ancient, as early records from many human societies all over the world have shown (Willey, 1979). In SSA, intercropping is considered as a traditional cropping system with the predominant crop combinations being maize, bean/cowpea and pumpkin (Matusso et al. 2014). According to Keating and Carberry (1993) and Midmore (1993), the advantage of intercropping over monoculture lies mainly in its proficient capture of resources. Reddy and Willey (1981) observed higher land, water and radiation use efficiency when pearl millet was intercropped with groundnuts. Sani et al. (2011) observed better land and water use in maize-sorghum intercrops. Kanton and Dennett (2004) observed better water use efficiency in maize and pea intercropping. On the other hand, results similar to those obtained by Gao et al. (2009) where no improvement of resource use have also been observed. This goes to show that a winning intercrop system combination is yet to be established.

Due to complexities in interspecies interaction (Malezieux et al. 2009), research in intercropping is still lagging behind in comparison to monoculture systems that boast of numerous systematic agronomic concepts and various exploratory tools such as crop models. Currently, most intercropping studies have focused on issues of yield, economy and food value of crops, basing conclusions on measures of final yield (Zhang and Li 2003). Little emphasis has been placed on the understanding of interspecific processes leading to these benefits. To enhance interest in intercropping research and possible farmer adoption, the science and attributes of intercropping need to be well understood. The aim of this paper is to review concepts in resource capture in intercropping, highlighting its advantages and possible drawbacks. There is a need to generate a large amount of comprehensive data, thus an overview of crop modelling for intercropping as a tool used to generate information was attempted. Since models in intercrop systems are still in their infancy, selected crop models that simulate resource use in multicrop systems are herein reviewed and limitations of the models are highlighted. The review is divided into two main parts. The first part addresses issues pertaining to intercropping and resource use, with particular attention to water and solar radiation, while the second part focuses on modelling intercrops.

Resource use in intercrop systems

The success of an intercrop has often been attributed to compatibility of component crops in resource utilization (Coolman and Hoyt 1993). According to Vandermeer (1989) growing of

two individual plant species or two populations together on the same land within the same time frame will result in either a positive or negative interaction for growth factors. These interactions can be classified as complementary, competitive or non-competitive.

In cases where resources (solar radiation, water and nutrient) are shared and are non-limiting, complementary interactions can be observed (Matusso et al. 2014). Growth and yield of either component crops is not affected by the presence of the other component crop. When intercropped plants compete for the same resources such that the inter-specific competition observed is equal to or higher than the intra-specific competition observed in the monocrop (Wubs et al. 2005), a negative and/or a competitive interaction will be observed. According to Zhang and Li (2003), a competitive system is most advantageous when the yield of the intercropped component crop is not as important as the main component crop. On the other hand, when competitive interaction is very high and yield penalties for both components are too large, Wubs et al. (2005) opined that monocropping would be more profitable than intercropping. In the case of a non-competitive system, both complementary and competitive interactions exist. For example, early plant growth of crops can be complementary for solar radiation but become competitive in a later growth stage.

Sub-Saharan Africa is significantly disadvantaged as it lacks a balance between natural resources and agricultural food productivity. Resources such as suitable land, nutrients and more importantly water, remain scarce. Their sustainable use can be achieved through intercropping. However, compatibility within existing and newly designed intercrop systems, and resource use are not thoroughly understood by researchers and intended beneficiaries such that information dissemination and farmer adoption remains low (Wubs et al. 2005). Ideally complementary systems are most desirable, however, this interaction is very difficult to observe in nature and under sub-optimum conditions present in rural farming areas (Matusso et al. 2014). Even if observed, there is always a danger of over-estimating gains. Complementary interactions can be achieved but this is often at the expense of increased management cost and labour requirements (Zhang and Li 2003). In the sections following, water, radiation and nutrients as limiting resources affecting crop production are discussed and it is point out how intercropping can efficiently capture and use them. More emphasis has been placed on water as it is the major limiting factor to crop production in SSA. For each of the reviewed resources, the influence of other resources is assumed to be non-limiting.

Water

In the last century global water use has been growing more than twice the rate of population increase and more regions are reaching the limit at which water services can be sustainably expanded and delivered (FAO 2013). According to the FAO's 2012 report on 'coping with water scarcity', it is projected that by 2025, absolute water scarcity (< 500 m^3 per year per capita) will affect 1 800 million people, and two-thirds of the world population could be under "stress" conditions (between 500 and 1 000 m^3 per year per capita). There is need to establish technologies that can produce more food per unit water consumed and intercropping has the potential (Willey and Osiru 1972; Ozeir-Lanfontaine et al. 1997) although the extent to which there are improvements varies enormously throughout literature (Morris and Garrity 1993; Seran and Brintha 2010). For instance, Oluwasemire et al. (2002) observed a 20% reduction in water use (WU) in a millet-cowpea intercrop system when compared to sole millet system. Jahansooz et al. (2007) observed no significant improvements in WU of wheat and chickpea intercrop system in comparison to the sole cropped components. According to Soetedjo et al. (1998) WU of late sown intercrop of field pea and canola was significantly higher (489.3 mm) than that of early and late sown pure stands of field pea (402.6 and 418.8 mm, respectively) and canola (425.8 and 408.1, respectively).

Crop water use (WU) is associated with the interaction of roots and their ability to scavenge water in the soil plus the capacity of the corresponding canopy to transpire the captured water efficiently (Morris and Garrity 1993). Water uptake is a function of rooting density distribution, soil-root system conductivities and soil available water (Ogindo and Walker 2003). Improved soil water uptake in intercropping has been attributed to the initial two factors. According to Anil et al. (1998) and Ogindo and Walker (2003), increased root density (temporal and spatially) and differences between rooting patterns (depth, width and length) in crop mixtures ensures that a larger volume of soil water can be exploited and thus improve water use efficiency (WUE). However, difficulties in studying root systems and root water extraction dynamics in multicrop systems have led to a few studies actually quantifying water uptake in intercropping let alone modelling below ground interactions. As a result, a more commonly used approach of quantifying WU and WUE in intercrops is studying canopy dynamics and the soil water balance approach which calculates crop water use as a residual (Morris and Garrity 1993).

Canopy dynamics that influence crop water use are related to crop species, plant canopy features and evapotranspiration (ET) (Allen et al. 1998). The shape, size and duration of a

canopy influence ET and its partitioning into soil evaporation (E) and crop transpiration (T) (Ogindo and Walker 2003; Morison et al. 2008). It is estimated that, under sole cropping, as much as 40% of rainfall can be lost through unproductive ways such as evaporation (soil and leaf) (Kinama et al. 2007) due to a smaller canopy and/or slower rate to attain maximum ground cover. The larger the canopy represented by leaf area index (LAI), the greater the proportion of water 'lost' through transpiration in exchange for carbon dioxide than soil evaporation (Seran and Brintha 2010). Morris and Garrity (1993) also articulated enhanced WU from extending duration of maximum LAI. Under intercrops, enhanced WUE was observed early in canopy development because maximum LAI was attained earlier in comparison to corresponding plots of sole crops (Oluwasemire et al. 2002;). When intercropped plants have different periods in phenological events, an additional bonus can be gained if the critical stages of water demand do not overlap; especially if one of the component crops has an extended period of canopy cover. On the other hand, if water stress occurs early during the season, increased plant cover can have a negative effect on biomass and yield attainment due to high interspecific competition. Morris and Garrity (1993) suggested use of small statured plants while Gaballah and Ouda (2008) emphasized that reducing plant density of the secondary crop species could lower competition.

In addition, mixing crop species or varieties with different canopy heights can result in alteration of canopy microclimates. Tall plants can act as wind breaks and as a shade for the understory and bare soil (Domingo et al. 1996). Reducing wind speed within the canopy results in a reduction in vertical momentum transfer of latent heat and boundary layer conductance (Grantz and Vaughn 1999; Stokes et al. 2006). In turn, leaf surface temperature approaches that of air temperature and relative humidity around the understory canopy are elevated (Innis 1997). This will then reduce evaporative demand from the soil surface and the immediate atmosphere around the understory canopy; reducing the rate of potential transpiration and ultimately limits photosynthesis. The understory is rendered less competitive than the dominant over storey for available soil water. Because of these modifications of understory microclimate it is expected that C3 plants, whose photosynthetic rate is saturated at lower light intensities, will not be adversely affected and should be recommended for use as the understory.

Although the differences in water use of intercrop and monocrop systems are not easily quantified, the direct effects of intercropping on yield in limited water conditions are well documented as highlighted above. Mechanisms that enhance WUE are strongly related to plant species (above-and below ground interactions), improved water uptake and modification

of immediate atmospheric characteristics. A multifaceted approach should be considered when studying WU in intercrop systems since systems are not one dimensional.

Solar radiation

Photosynthetically active radiation (PAR) is light in the waveband of between 400 and 700 nm and a chief determinant for biochemical processes in photosynthesis for the production of biomass in plants. As it stands, PAR is a flux of electromagnetic energy that must be used instantaneously as it cannot be stored for later use. Consequently, PAR can be limiting and competition for this resource between neighbouring plants is often high. Campillo et al. (2012) stated that out of 100% of incident on the leaf, only 5% was converted into biomass by leaves while 60% is not absorbed, 8% is reflected and transmitted, 8% is lost through heat dissipation and 19% is used in other metabolic processes which did not constitute direct biomass production. The efficiency with which plants produce dry matter depends, therefore, on the fraction of intercepted PAR and mechanisms of carbon fixation (Black and Ong 2000). This has been termed radiation use efficiency (RUE). According to Campillo et al. (2012), RUE depends largely on several canopy factors such as canopy size and duration, leaf angle, properties of leaf surface (leaf hair and waxy layers that affect light reflection), thickness and concentration of chlorophyll, size and shape of leaf phyllotaxis (vertical stratification) and sum and distribution of direct and diffused solar radiation. In addition, Keating and Carberry (1993) stated that canopy diversity can influence radiation interception in terms of spatial and temporal dimensions.

Similar to WUE, intercropping has been shown to improve RUE and its extent is also attributed to plant-plant interactions (Awal et al. 2006; Tsubo et al. 2001). In the first instance, Keating and Carberry (1993) acknowledged that the main mechanisms which aid in improved RUE were also linked with spatial and temporal arrangements were issues related to hastening attainment of adequate LAI and LAI duration gave precedence (Tsubo et al. 2001). In addition to these, the effect of discontinuous canopy profiles, that is mixing of crop species with different growth habits, on the understory microclimate has been observed to influence RUE (Faurie et al. 1996).

Radiation interception in intercrop systems can further be improved by horizontal and vertical canopy variations introduced by species diversity such as maturity date, geometric arrangement, height and at times plating dates (Black and Ong 2000). The transmission and reflective properties of over storey canopy affects the delivery and quality of light to the

understory. Over storey intercepts direct light while the understory intercepts diffused PAR. The downward attenuation of light within a canopy is presented in the form of Beer's Law (Monsi and Saeki, 1953):

$$I = I_0(1 - e^{-kL})$$

where I is the intercepted light, I_0 is the incoming radiation (MJ m-2), L is the LAI and k is the extinction coefficient of the canopy. Extinction coefficient is the attenuation of PAR through a canopy and small values mean deep penetration of PAR into the canopy while large values mean the inverse. According to Breda (2003) k is a function of leaf angle distribution and leaf azimuth, stand structure and canopy architecture and varies with variety, species and season. In an ideal scenario, the dominant crop should have erectophile leaves, reducing k which in turn allows deep penetration of light to the understory. To date, research has shown that scientists have successfully manipulated genes controlling an erect leaf pattern in major cereals like maize (Kanton and Dennet 2003) and wheat (Reynold et al. 1999). However, Reynold et al. (1999) indicates that architectural improvements have been to the demise of leaf area index since these improved genotypes were associated with smaller leaves. To increase PAR penetration, a lot of plant canopies have evolved into having irregular leaf patterns that increase gap fractions within the canopy. Even though the distribution and amounts of gap fractions vary between plant species and varieties within species, when planted in appropriate proportions and arrangements these plants can allow some amounts of direct PAR to reach the understory. Therefore, issues related to genotype selection and populations, which are often a grey area to resource poor farmers, are important in distribution of PAR within the intercrop canopy.

The physiological and morphological effect of shading on understory plants in intercrop systems has not been extensively investigated. As light penetrates a canopy, the composition within the spectrum changes altering the quality of light reaching the understory. Leaves intercept more red than far-red light. Hence the ratio of red to far-red light decreases within the canopy (Pushnik et al. 1987). Top layers of a canopy intercept red and blue light and transmit far-red, orange yellow and green light. Depending on the k, the ratio of red: far-red decreases and this can induce stem elongation, reduces branching and can stimulate early flowering of the understory (Casal 1988). The response to shading also depends on differences in carbon fixation pathways (Sage and McKown 2006). For C3 plants, photosynthetic rates increase sharply as PAR increases from deep shade to 50% full exposure then it peaks (point of saturation) and remains constant. In contrast, C4 plants only become

saturated at full sunlight (Fitter and Hay 2002). Crop mixtures with C4 plants being the dominant and C3 as the intercrop understory are guaranteed of improved RUE because maximum photosynthesis and biomass is maintained by the C4 and while a proportion can be maintained by the C3 growing under low PAR. Within SSA, farmers have been mixing C4 cereals and C3 legumes for decades (Matusso et al. 2014). That being said, researchers can positively influence the rate of adoption of new and improved cereal-legume intercrop systems by tapping into existing indigenous knowledge systems.

Crop modelling in multicrop systems

Research methods in agriculture are now vast and multi-disciplinary, and possess many tools for accurate determination of relationships within a production system. As it stands, systemic agronomic concepts have been well defined and many continue to be postulated. However, many of these concepts have been built on monocrop frameworks and do not fit into the current concept of agro-diversity through intercropping. Although intercropping is an ancient form of food production, according to Malezieux et al. (2009) research methods are not advanced enough to ensure the availability of information for sustainable food production. In particular, crop simulation models (CSM) are now widely recognized as useful tools that examine cause and effect relationships in crop production. Only a few CSMs are adapted to simulate intercrop systems. For those that exist, the majority still ignore spatial heterogeneity of plant mixtures, and streamline the system into a single dimension (Nair et al. 2012). To effectively introduce intercrop packages as a way of ensuring sustainable food security a lot of relevant data need to be generated and synthesized.

Crop simulation models analyse systems by defining borders and distinguishing major components. They describe changes within the components using mathematical equations and then link obtained outputs to obtain a representation of the system (van Ittersum et al. 2003). By definition, CSMs are computerized representations of crop growth development and yield simulated through mathematical equations as functions of soil and environmental conditions, crop species and genotype, and management practices (Hoogenboom et al. 2004). In essence, CSMs are used to address "what if" and "when" type of questions with regards to yield as the main response of interest. They vary, in terms of application, fundamental structure and core development (Sinclair and Seligman, 1996). According to the amount of data and knowledge that is available within a particular field, models with different levels of complexity have been

developed (Cheeroo-Nayamuth 2000). Since early studies started using CSMs, two approaches that are mechanistic and empirical have emerged as dominant model types.

Mechanistic models are built with the intention of describing systems' bio-physical processes in a somewhat complete mathematical description. Mechanistic models (explanatory models) consist of large sets of quantitative data of mechanisms and processes that guide the behaviour of the system. To explain the system, the models separately quantify processes and mechanisms of the system (Miglietta and Bindi 1993). The model will then assemble a simulation by integrating these various components. According to Fleisher (2009) the nature of mechanistic models is reductionistic as it uses mechanisms from high level (canopy) down to low levels (cellular processes). The majority of CSMs use the mechanistic approach to model crop systems. For monocrop systems, these models are already considered complex but they are vibrant at explaining processes. In order to simulate interactions in intercrop systems there is a need for a good understanding of spatial and temporal concepts of resource sharing and how these alter mechanisms and processes at plant level. Malezieux et al. (2009) suggested that mechanistic models could capture this plasticity. This, however, complicates the model further and threatens to introduce large volumes of mathematical error.

On the other hand, less robust models do exist and these often fall under empirical or descriptive models. Empirical models are direct descriptions of observed data used to estimate final yield and are generally expressed as regression equations with one or a few factors (Thornley and Johnson 1990). These models are said to simulate the behaviour of a system in a simple way (Miglietta and Bindi 1993). They do little to attempt to reflect mechanisms that cause the observed behaviour in a system. In a highly homogeneous system where variables are not allowed to fluctuate (greenhouse production systems) empirical models can be used. Under field conditions, large variations in soil environments, weather conditions and crop management practices can result in poor simulation of crop growth. That being said, their minimal use in multicrop model could be due to the way they inadequately capture plant interactions and alterations. However, they still have a place in data exploration and extrapolation.

Approaches for modelling resource use in intercropping systems

Intercrop models can be divided into three groups depending on spatial compartmentalization of the simulated scene. The first approach is consistent with de Wit (1978) and de Wit et al. (1970) principles and also includes models such as the Agricultural Production Systems

sIMulator (APSIM) (Carberry et al. 1996) and Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al. 2003). These models belong to the 'School of de Wit' models. For this approach, the soil plant atmosphere continuum (SPAC) is often represented as a single or two layer systems with emphasis placed on the dynamics of the system rather than on the spatial heterogeneity of it. Scale expressions of biophysical exchanges at the leaf level are linked with those at the canopy level and models often assume the 'big leaf' structure (Malezieux et al. 2009). To describe the dynamics of the system, modules are added to the core source code (Jones et al. 2001) of the model. Plug in and plug out modules like APSIM (McCown et al. 1996) increase functionality of the model and reduce the complexity of the actual model. The most appealing feature is the dependence of limited number of variables that can be used which often have a linear relationship. Disadvantages to this approach are that it often ignores gradients within the canopy and does not consider counter energy transfers and partitioned fluxes occurring between the canopy and soil. Another weakness to this approach is that both linear and non-linear algorithms used to calibrate and validate do not always relate to measurable physiological or physical quantities since the simplified algorithm might not capture differences within canopy. Other examples of models that fall into this category include Cropping System Simulation Model (CropSyst) (Caldwell and Hansen 1993).

The second approach to modelling resource use is by describing the intercrop as a series of discrete crop based points with flow of energy and mass between each component. According to Gu et al. (1999), these models can be described as multilayer models where vertical canopy structures/layers are considered. For each layer, biophysical exchange rates are calculated and canopy scale fluxes are obtained by integrating them over the depth of the canopy. Models using this approach can be either incomplete or complete. According to Gu et al. (1999), some variables (solar radiation, wind speed) sensitive to canopy features are differentiated vertically while less sensitive variables (e.g., carbon dioxide concentration) are held constant throughout the depth of the canopy. Sensitivity of complete multilayer models makes them robust in accounting for the smallest factors that can have a large effect on the system. An advantage of the multilayer method is that spatial discretion within a heterogeneous canopy can be accounted for and point variations in the field. However, this approach is complex, requiring large quantities of data making it time consuming and costly. Examples of such models include the Water Nutrient and Light Capture in Agroforestry Systems (WaNulCas) (van Noordwijk and Lusiana 1999).

21

The third approach gives a realistic description of the complex dual species canopy (3D structure). Emphasis is placed on canopy and light attenuation since PAR is one of the most important environmental factor that is highly competed for in multicrop systems. Also, in functional-structural models of plants and plant communities light can be used to simulate key biophysical processes involved in plant growth and development, such as photosynthesis, evapotranspiration, and photomorphogenesis. An advantage of this approach is that it captures variation in the horizontal and vertical and diagonal direction. However, Brisson et al. (2004) noted that it was difficult to account for system dynamics due to complex dynamics at organ level and their interaction as well as interactions at whole plant level.

Description and parameterization of selected crop models for multicrop systems

Models that simulate multicrop systems vary in their complexity and approach. The models discussed in this review use a daily time step which varies from tree-crop models that use monthly and yearly time steps. According to Nair et al. (2012), daily time steps improve the accuracy of model calibration. However, this input in simulation can fail to capture precise moments when plant processes are altered due to sudden changes in crop responses (e.g., effect of intermittent water stress on photosynthesis). On the other hand, CSMs might be designed in this manner to reduce intensity of data quantity and cost of experimentation.

Above ground interactions

Above ground interactions are modelled using dynamic or mechanistic approaches. With the exception of Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMANAC) (Kiniry et al. 1992), presented models use mechanistic approaches (Table 1). Crop growth or biomass production can be simulated using three modules which are 1) carbon driven, 2) water driven, and 3) radiation driven. Models presented here are either water driven (AquaCrop) or radiation driven (CERES (Ritchie et al. 1998), Simulateur multidisciplinaire pour les Cultures Standard (STICS) (Brisson et al. 2004), APSIM, ALMANAC, WaNulCas and Soil Water Balance (SWB) (Annandale et al. 1996). According to Nair et al. (2012), RUE is the most straightforward approach for simulating biomass production. It is argued that the relationship between radiation and biomass accumulation is inconsistent across crops, location and year (Steduto 2006). In addition, the slope of the relation between biomass and radiation is sensitive to water and nutrient stress and could over– or under–estimating biomass production at the expense of radiation capture. A more suitable way could be using a

conservative approach like the one employed by AquaCrop. Biomass production in AquaCrop is linearly proportional to transpiration through a water productivity (WP) parameter (Steduto et al. 2007). Water use in intercropping remains a complex area of research as it is very difficult to partition between components. Multicrop models have not yet advanced to the stage where WP can be partitioned between the components. The issue is not in the mathematical relationship but the parameters required as inputs for calibration. As it stands, AquaCrop does not have the capacity to simulate resource use and growth for intercrop systems. Its main role within this article is to use it as a point of comparison for data requirement. In this regard, simulating biomass production through radiation remains the dominant way canopy growth is simulated in multicrop models.

That said, in radiation driven models, processes in above ground biomass production and partitioning are divided into three levels; firstly, light interception and estimation of radiation capture, secondly conversion of light into biomass and thirdly, it's partitioning. With the exception of CERES, light interception for included models is accounted for by a modified Beers' Law which allows for partitioning of intercepted radiation between component crops (Spitters and Aerts 1983) (Table 1). Biomass partitioning seems flexible for these models so as to capture species diversity. Functionality of a model often detects what environmental stress factor can be addressed on various plant growth and developmental stages. In multicrop systems, stress can occur incognito due to complex interactions between component crops. Models like AquaCrop, STICS, CERES, APSIM, ALMANAC and WaNulCas include stress factors for water, radiation and nutrients as factors that can directly affect crop growth.

Table 1 A comparison of above ground parameters and process simulation across selected multicrop simulation models.

	APSIM	STICS	ALMANAC	CERES-models	AquaCrop	WaNulCas	SWB
Approach Canopy growth and interaction	Mechanistic ID light interception with two layers	Mechanistic ID geometric canopy	Dynamic ID light interception with two layers	Mechanistic 1D light interception with two layers	Mechanistic 1D Canopy cover for transpirational loss	Mechanistic 1 D light interception	Mechanistic 1/2D light interception
[1]Biomass partition.	Species dependent	Species dependent	Species dependent	Species dependent	Species dependent		Species dependent
Radiation penetration	Mixed Beer's Law	Mixed Beer's Law	Mixed Beer's Law	Beer's Law		Leaf area indices of tree and crop	Mixed Beer's Law
Stress factors affecting canopy growth	Light Water Nutrient	Light Water Nutrient	Light Water Nutrient	Light Water Nutrient	Water	Light Water Nutrient	Light Water

[1] Biomass partitioning.

Below ground interactions

As often referred to, below ground interactions in multicrop systems have not evolved far enough to adequately partition direct and indirect effects within the system. Methods of simulating growth and interactions largely remain one dimensional with many sublevels. In the case of presented models, WaNulCas has attempted to go a step above 1D representation of root interactions (Table 2). Within this model, below ground system is separated into four horizontally distributed spatial zones within which water and nutrient balances between components can be explained (van Noordwijk and Lusiana 1999). Overall, the reviewed models use biomass partitioning coefficients to regulate above and below ground growth. Other inputs used to explain water and nutrient balances include root volume length, which at times is corruptible due to errors in sampling and soil characteristics.

Table 2 A comparison of below ground parameters and process simulation across selected multicrop simulation models.

	APSIM	STICS	ALMANAC	CERES-models	AquaCrop	WaNulCas	SWB
Root interaction	------------------------------------1D root interaction with n layers---					2D root interaction (depth and distance from stem)	1D root interaction with n layers
Root growth	---Canopy size influences root growth--						
input parameters	Root length volume (RLV) in soil with n layers and Maximum rooting depth,	-	Root :shoot ratio and maximum rooting depth	Root length volume (RLV) in soil with n layers and Maximum rooting depth,	Root water extraction front, effective rooting depth and maximum rooting depth	Root length volume (RLV), Maximum rooting depth	Root length volume (RLV) in soil with n layers
Root interaction	Separate components – no direct interaction	Separate components – no direct interaction	Separate components – with/ without direct interaction	Separate components – no direct interaction	-	16 components with direct interaction	Separate components – no direct interaction
Factors affecting root growth	Water and nutrient, and biomass partitioning coefficients	Species input coefficient for the temperature dependence of root growth and water status	Water and nutrient	Water, nutrients biomass partitioning coefficients	-	Water and nutrient	-

Under monoculture, the study of below ground interaction remains challenging although numerous empirical and theoretical methods do exist. The extrapolation of such methods in intercrop systems remain somewhat redundant because of the uncertainties in root interaction that could arise. Rubio et al. (2001) suggested the use of geometric models such as *SimRoot* (Lynch et al. 1997) as an alternative of numerical estimations of depletion volumes and depletion overlaps in complex root systems such as those in multicrop systems. That being said, incorporating models like *SimRoot* into the current set of reviewed models could improve predictions of below ground interactions. This would, however, further increase the complexity of these models.

Soil and climate inputs

Across the selected models, description of the soil environment is somewhat generic (Table 3). For the climate parameters, table 4 shows that reference evapotranspiration is calculated using different methods. An acceptable and generally agreed upon way of calculating ETo is the FAO-Penman–Monteith method (Allen et al. 1998) as it is more transferable across locations. Within CSM, crop growth and production is a function of weather and soil conditions in relation to cultivar and management practises. Since resource utilization in intercrop systems is generally complex to investigate, accurate capture of all input parameters of both soil and weather is very important so as to improve model performance and prediction.

Table 3 A comparison of soil parameters required for simulation across selected multicrop models

Soil parameters	APSIM	STICS	ALMANAC	CERES-models	AquaCrop	WaNulCas	SWB
Generic parameters	Soil profile, Soil chemical properties, Soil texture, Field capacity, Saturation point, Permanent wilting point, Total available water.						
Bulk density	√	√	√	√	√	√	√
Hydraulic conductivity (K_{sat})	√	√	√	√	√	√	√
Run-off co-efficient		√	√	√	√		
Slope	√					√	√
Soil albedo		√	√	√		√	

Table 4 A comparison of climate parameters required for simulation across selected multicrop models

Climatic parameters	APSIM	STICS	ALMANAC	CERES-modules	AquaCrop	WaNulCas	SWB
Generic parameters			Tmax, Tmin, Daily rainfall, Daily radiation				
Wind speed	√	√		√	√	√	√
Humidity	√	√		√	√	√	√
ET$_O$[1]	PT[2]	PT, EB[3]	PM[34]	PT, FAO-PM	FAO-PM[5]	FAO- PM	FAO-PM

[1]Reference Evapotranspiration, [2]Priestly and Taylor equation (Priestly and Taylor, 1972), [3]Energy Balance method (Brisson et al., 2003) [4]Penman-Monteith equation (Monteith, 1965), [5]FAO Penman-Monteith (Allen et al., 1998).

Current drawbacks and future directions

Although intercropping has been used traditionally for many years, it is still poorly understood from an agronomic perspective. Simultaneous growing of two or more crop species results in complex interactions which warrant better and more intimate management strategies. This often increases the complexity of management over and above that given to monocrops. For instance, issues related to different pest and disease control and harvest time can result in additional cost and labor requirements. Rusinamhodzi et al. (2012) stated that it was imperative that farmers were given access to improved varieties which are tolerant to pests and diseases so as to minimize cost of production in intercropping. Differences in harvest time can be overcome by adjusting planting time of component crops such that harvest overlaps. Other management decisions that affect the success of intercropping include crop proportions and geometric designs.

It has been highlighted in previous sections that crop proportions have a strong influence on resource competition and use within the intercrop. Improving our understanding of crop proportions and the static relationships within set boundaries of resource availability, capture and partitioning can result in improved system and yield performance. Although work has been devoted to simulating abiotic interactions in multicrop systems, more efforts need to be focused on better understanding of interactions of resources. This requires good understanding of above- and below–ground processes. In addition, the physiological and morphological plasticity of above- and below–ground structures should be appreciated and well understood since these changes can alter processes of resource capture and use and subsequent productivity of the system (Stockle 1999). Crop simulation models should be integrated with the option to simulate best component proportions and geometry within a

given range of resources as it is clear that this has a strong bearing on resource use and competition.

Modeling resource use in multicrop systems is still in its infancy as only a few models exist. Although existing models can simulate interactions, the degree of precision is questionable because of the general poor understanding of system dynamics within multicrop systems. Presently, the core structure of most multicrop simulation models are based on monocrop models, yet these systems are different containing more complex sub-level interactions (Codling and Dumbell 2012). This problem is worsened and confounded by inaccurate data inputs and rigid parameterization. Therefore, mathematic equations within multicrops modeling should be developed alongside multicrop theories to account for these errors.

The desire to re-introduce intercropping in resource poor regions of SSA is aimed at intensifying crop production at a point scale and/or promote and expand profitable farming enterprise for improved food security. Crop simulation models have been used to great satisfaction for farm management at point scale. As it stands, change in spatial scale can affect model precision due to increase in data quantity and spatial and temporal distribution of resource capture, land and micro-climate. According to de Wit and van Diepen (2007) improved soil water balance estimations in WOrld FOod STudies (WOFOST) (Supit et al. 1994) was made possible by integrating observations from coarse resolution satellite microwave sensors. Sehgal and Sastri (2005) observed good simulation of yield variations across district scale when remote sensing (RS) and geographic information system (GIS) tools were assimilated into wheat growth simulator model (WTGROWS) (Aggarwal et al. 1994). Sehgal and Sastri (2005) concluded that RS and GIS can improved the derivation of crop phenology and biophysical products such as LAI and intercepted PAR for large catchment areas.

Conclusion

Despite the advantages of intercrop systems in resource utilization and ultimately food production and security, conventional agronomic research has largely focused on monocrop systems. The science behind intercropping should be shared with farmers so that they themselves can manipulate crop management factors. Information of crop arrangements and proportion as factors that affect intercropping systems is still lacking as shown by the shallow understanding of ecological interactions between species in mixed systems. Multicrop

systems can be simulated but this is done by only a handful of models. The relevance, but relative limitation of the concepts and existing tools of systemic agronomy in representing and simulating intercrop systems and their properties certainly reveal the need to find new representations to account for the particular processes brought into play. As shown in this review, the numerous mechanisms involved in species mixing highlight the need to deal with their complexity by combining concepts from diverse disciplines (agronomy, physiology and ecology), although the necessary link with ecology largely remains to be constructed.

Acknowledgements

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CHAPTER 3

SEED PERFORMANCE OF SELECTED BOTTLE GOURD (*LAGENARIA SICERARIA* (MOLINA) STANDL.) LANDRACES

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ABSTRACT

Bottle gourd (*Lagenaria siceraria* (Molina) Standl.) is a useful crop to include in climate change adaption strategies for agronomy. However, diversity in plant and seed forms makes it difficult to predict performance under field management. There is a dearth of knowledge on the relationship between seed morphology and seed performance, namely, germination and early establishment of seedlings. This led to a need to evaluate seed morphology of different bottle gourd landraces and its effect on seed quality as defined by germination and vigour. Six mature fruits of different bottle gourd landraces were collected from subsistence farmers and seeds from each fruit were morphologically characterised. Standard germination test, root: shoot ratio, seedling fresh mass, seedling dry mass, germination velocity index (GVI) and electrical conductivity were used to establish seed quality and vigour. Although all traits were significantly different, most of them were not good indicators of seed quality. Seed coat thickness isolated varieties by provenance and was inversely proportional to root: shoot ratio as a measure of seedling establishment. It is concluded that bottle gourd seed morphology could be a useful trait for selection of planting material in the context of seed germination as a trait.

Key words: bottle gourd (Lagenaria siceraria); landrace selection; seed quality; seed morphology

INTRODUCTION

Food security has become a crucial issue in rural Africa due to the possible effects of climate change, reduction in arable land, as well as increase in human population and poverty. In the past, research was mostly undertaken to enhance productivity of selected crops suitable for high potential areas, and the so called traditional/orphaned crops that are especially appropriate for low potential areas were abandoned (Mayes *et al*. 2012). However, most rural farmers were unable to afford the high input costs associated with such innovations, and production was affected by numerous biotic and abiotic constraints (Fader *et al*. 2013). These initiatives were, therefore, unsuitable, and increased the poverty gap for most subsistence-based rural farmers. Before the turn of the century, the need to find cheaper alternatives to green revolutionary farming for subsistence farmers increased (Laswai *et al*., 2000). Research has since refocused its efforts on alleviating poverty in rural communities by using strategies relevant and indigenous to these communities. One such strategy employed was the re-introduction of neglected underutilised crops such as bottle gourd (Schipmman, 2011).

Bottle gourd is one of the most important crops in the cucurbitaceae family, although it is considered as a poor man's crop due to the socio-economic restrictions governing its production and use. It has a pan-tropical distribution with regional economic importance and is used as a vegetable, container, musical instrument or float while its seeds are used for oil and protein. A lot of information is known on the medicinal aspects of bottle gourd (Milind and Satbir, 2011); however, its potential as a possible food security crop has been lowly documented. In nature, bottle gourd exhibits great morphological and genetic variability (Given, 1987). This alone could indicate its wide environmental adaptation (Koffi *et al*., 2009). The plant also demonstrates an indeterminate growth habit when there is enough supply of water. This allows farmers to have a constant supply of fresh green leaves for consumption and animal fodder. Young immature fruits are consumed in the same manner as pumpkin fruits, while the seeds are a rich source of essential amino and fatty acids (Loukou *et al*., 2007; Koffi *et al*., 2009). Bottle gourd does not require complex field management practices. It grows well with small amounts of nitrogen fertiliser and it is a natural weed smother (Koffi *et al*., 2009). It is often intercropped with cereal crops and can act as a live mulch (Ouma and Jeruto, 2010). Given such benefits, it is surprising that bottle gourd is the cucurbit with the least amount of scientific research directed at enhancing utilisation, let alone productivity. One important aspect in crop production that is often overlooked by many

41

resource limited farmers is seed quality. There is limited and diffused information on seed technology of bottle gourd (van Molken *et al*., 2005; Yetişir *et al*. 2008).

Seed quality has been described as a multiple concept comprising several components (De Geus *et al*., 2008; Powell *et al*., 1984; Thompson, 1979). Hampton (2002) described seed quality as the standard of excellence in certain characteristics that will determine performance when the seed is either stored or sown. Seed germination capacity and vigour are, therefore, the key measures of seed quality (Bewley, 1997; ISTA, 2003). When varieties occur in variegated seed forms, it is important to determine whether or not such variegation affects seed performance in terms of germination and vigor. Many scholarly articles have reported on the effect of seed size, colour, seed coat morphology and dimorphism (single plant produces two seed types with different morphology) on seed quality in several species (Bewley, 1997; Jakobsson and Eriksson, 2000; Iossi *et al*., 2005; Camelia, 2011). It is difficult, however, to conclude that results obtained from these studies can be superimposed on bottle gourd, owing to the vast morphological variegation within a single species.

Practical considerations have shown that large seeds have better germination capacity and vigour, and will produce more competitive seedlings than smaller seeds, hence high seed quality (Pettigrew and Meredith, 2009). The possible effect of seed size on seed quality (germination and vigour) is associated with the longer duration and the rapid provision of energy by the large endosperm to the developing seedling (Jakobsson and Eriksson, 2000). On the other hand, research has also demonstrated that there is an association between seed physical parameters such as seed coat thickness (de Souza and Marcos-Filho, 2001) and endosperm size (Chastain *et al*., 1995) with seed quality. Of interest is the effect of seed coat thickness on seed electrical conductivity, which is another measure of seed quality.

Electrical conductivity test measures the amount of electrolyte leakage from seed during imbibition. This leakage of electrolytes is due to reorganization of membrane components and conformational changes occurring in cell membranes upon drying and ageing of seeds (Shereena and Salim, 2006). Increase in conductivity has been found to be correlated with a decrease in seed quality. The seed coat acts as a barrier restricting the diffusion of nutrients and electrolytes from the seed into the soil (Beresniewicz *et al*. 1995). However, this will depend on the seed coat integrity.

Currently, bottle gourd is considered as a neglected underutilised species (NUS) with regional importance in Africa. It has immense benefits, but possible widespread adoption is restricted by the lack of evidence regarding its morphology, husbandry and nutritional

benefits for improving human nutrition. The objective of this study was to review the bottle gourd and evaluate possible variation in seed morphology of different landraces in relation to seed quality on the basis of germination and vigour.

History of bottle gourd

Bottle gourd (*Lagenaria siceraria* (Molina) Standl.), also known as calabash gourd or white flowered gourd plant, is a member of the Cucurbitaceae family, Cucurbitoideae sub family, and Benincaseae tribe (Richardson, 1972). The family Cucurbitaceae comprises 118 genera and 825 species (Schlumbaum and Vandorpe, 2012). The genus *Lagenaria* consists of five other wild species, namely *L. brevifilora* (Benth) Roberty, *L. rufa* (Gilg) C Jeffrey, *L sphaerica* E Mey, *L. abyssinia* (Hook. F.) C Jeffrey and *L. guineensis* (G Den) C Jeffrey, of which *L. siceraria* is the most cultivated (Erickson *et al*., 2005). Within the species *siceraria*, two morphologically distinct sub-species of bottle gourd have been recognised *viz. L. siceraria* ssp. *siceraria* and *L. siceraria* ssp. *asiatica* (Heiser 1979). Bottle gourd has a bi-hemisphere distribution with regional and sub-regional importance (Yetişir *et al.* 2008). Archeological findings have shown that the independent use and possible cultivation of the crop started from around 9 000 to 10 000 BP (before present) in the Americas (New world), 6 000 – 10 000 BP in East Asia and 4 000 – 5 000 BP in Africa. Based on this archeological evidence, bottle gourd is said to be one of the first species domesticated by humans (Erickson *et al*., 2005; Clarke *et al*., 2006; Schlumbaum and Vandorpe, 2012).

Bottle gourd has long attracted an interesting debate about its centre of origin (Harris, 1967; Richardson, 1972). In that debate, there is strong evidence, that bottle gourd originated from Asia or, despite the lack of early remains but commonly thought, Africa south of the equator to be more precise (Whitaker, 1971). The centre of origin of a crop can be described as the area containing the highest number of the wild relatives of that crop and its subsequent domestication. Both continents contain wild species of bottle gourd; however, the discovery of an additional wild indigenous species (*L. breviflora*) in Zimbabwe in 2004 by Decker-Walter *et al* (2004) reinforced the latter hypothesis of Africa as the centre of origin.

The origins and subsequent dispersal of bottle gourd still perplexes many scientists. The crop is said to have reached Asia and the Americas about 10 000 to 8 000 years ago, possibly as a wild species whose fruits and seed had floated across the seas and oceans with the aid of currents (Decker-Walter et al. 2004; Erickson et al., 2005). Whitaker and Carter (1954) demonstrated this hypothesis to be possible through experiments that showed that bottle gourd

fruit still contained viable seeds even after floating in sea water for more than 7 months. Upon reaching Asia and the Americas, the wild bottle gourd is said to have evolved in to two subspecies, L. siceraria ssp. siceraria and L. siceraria ssp, asiatica, respectively (Schlumbaum and Vandorpe, 2012). It has been hypothesised that multiple domestications of bottle gourd should have occurred. Through DNA analysis and comparison, it is now certain that two separate events of domestication occurred (Clarke et al., 2006; Yetişir et al. 2008; Schlumbaum and Vandorpe, 2012).The first in Asia around 10 000 BP, then in Africa at around 3 000 BP (Richardson, 1972).

Botany

Bottle gourd is an annual herbaceous plant with a prostrate or branching type growth habit. The leaves are alternate and variable, and tendrils (Fig.1) are almost always present. Flowers of *L. siceraria* are monoecious in nature, where solitary male and female flowers are found on different plant axis of the same plant, thus cross pollination is highly favorable.

Fig. 1. Different bottle gourd plants. Seed shape of fruits displayed: A and D – Calabash; B – Cucumber; C – Bean shaped; E – Pumpkin; F and G – Cylindrical; H – Club.

Dioecious and andromonoecious sex forms bearing hermaphrodite flowers also exist in wild, non–cultivated types. Like most cucurbits, the sex ratio (male: female) for bottle gourd is high (Sivaraj and Pandravada, 2005). The proportion of male to female flowers has been shown to affect yield significantly. According to Desai (2011), environmental conditions (precipitation, temperature and light intensity) and various growth regulators (Auxins, ethylene, gibberellic acid etc) can be used to alter this ratio.

Bottle gourd fruit vary widely in shape and size, and this is within or among cultivars (Sillitoe, 1983) (Fig. 1). According to Morimoto *et al.* (2005), among the six known species, *L. siceraria* exhibits the widest variations in fruit shape; these are either long, cylindrical, necked, oblong flat or round, conical pyriform to club shaped, while skin texture varies from warted to smooth (Fig. 1). Fruit size varies from 5 to 40 cm wide, and 20 to 90 cm long (Sivaraj and Pandravada, 2005). Seed forms also differ according to shape, size, presence or absence of frills and seed lines, and seed coat surface texture (Sillitoe, 1983). The large genetic variability in bottle gourd is a much desirable trait as it also reflects on its wide adaptation it possesses (Sillitoe, 1983).

Uses and opportunities as a food security crop

Bottle gourd is mainly grown as a vegetable for human consumption. However, hard dry shell is often used in utensil and instrument making, hence calabash gourd (Loukou *et al.*, 2011). Furthermore, in India different plant parts, especially the fruit juice, can be used as medicine to cure stomach elements (Haque *et al.*, 2009). In many parts of the world the young green fruit is a popular cooked vegetable (Prasad and Prasad, 1979). In Southern Africa, the leaves are commonly consumed as a vegetable relish and at times mixed with other vegetable plants. They can also be added fresh to maize porridge (Grubben and Dento, 2004). The leaves can also be dried and stored for later use in the off season. In Asia, bottle gourd is used as rootstock for watermelon (scientific name) against soil-borne diseases and low soil temperature (Yetişir *et al.* 2008). In West Africa, mature seed of bottle gourd are roasted and ground to a paste, which is used to thicken sauces (Loukou *et al.*, 2011). In Botswana, Zimbabwe and South Africa, oil is extracted from the seed and used as an alternative to vegetable oil (Grubben and Dento, 2004) while the defatted cake can be used as a protein supplement. According to Loukou *et al.* (2011), the untapped potential of bottle gourd lies in the use of its seed kernel in the food and livestock feed industry; it is a rich source of oil (45%) and protein (35%).

In Southern Africa, similar to many developing countries, there is a high incidence of protein-energy malnutrition (PEM) in rural and urban populations, with the consumption of a predominantly maize based diet. It has been observed that there are approximately 38.6 percent stunted, 28.4 percent underweight, and 8 percent wasted children under 5 years old, all symptoms of kwashiorkor and marasmus. Although modern science has been able to boost the proportion of essential amino acids (lysine and tryptophan) in maize, the penetration into rural communities is still slow. Due to the inadequacy of maize based diets in supplying much needed essential amino acids the use of bottle gourd seed or defatted seed cake could boost availability as it contains most if not all of the essential amino acids.

According to Axtell and Fairman (1992), oil extracted from bottle gourd seed is rich in fatty acids (high in essential fatty acids, chiefly linoleic acid) and sterolic compounds (eg spinasterol) and is comparable to semi-siccative oils such as sunflower or grapeseed oil. The human body is not able to produce essential fatty acids on its own, so it is necessary that one consumes a diet rich in these crucial building blocks in order to maintain a healthy body. The use of oil extracted from bottle gourd seed could possibly provide resource limited farmers, and more importantly pregnant and lactating women, and children under 5 years old, with much needed essential fatty acids. Therefore, bottle gourd has potential to contribute to food security and plug dietary gaps.

Other than the provision of essential fatty and amino acids, the young edible fruits of bottle gourd are rich in dietary fiber with very low fat and cholesterol levels and have about 80% water content in its flesh. It contains some amount of iron content and is rich in vitamin B and vitamin C and also contains sodium, potassium and essential minerals as well as trace elements. High sodium and potassium content makes bottle gourd an excellent vegetable for hypertension and hypertension patients (Axtell and Fairman, 1992).

Livestock also play a significant role in most small-scale farming systems throughout the world. Despite the importance of livestock, poor livestock nutrition is a common problem in developing countries, and a major factor affecting the viability of livestock industries in these countries (Chikwanha, 2006). Observations in rural communities of Zimbabwe have shown that leaves, fruit and seed of bottle gourd are being used to supplement livestock grazing and feed resources (Chikwanha, 2006). Cattle have been observed consuming young tender leaves of bottle gourd, while goats and pigs prefer the fruit (Chikwanha, 2006). In the wake of increased rural malnutrition, rural farmers still have to cope with high cost of livestock feed, depleting pasture lands and water resources. Increasing production and use of bottle gourd to

compliment and augment feed could assist in increasing availability of nutritious feed to livestock, thus increasing food security within these regions.

On the other hand, bottle gourd, like all cucurbits, produces trace quantities of complex substances known as cucurbitacins, which produce a distinctive aroma and help protect the plant from insects and animal predators (Chandra, 2010; Puri *et al.*, 2011; Sukhlecha, 2012). Cucurbitacins are bitter compounds and have a tetracyclic triterpenoid structure. Bitter bottle gourds have abnormally high levels of these cucurbitacins than the less bitter types. The amount of bitter juice that is consumed decides the level of toxicity. The ingestion of 50 ml of bitter bottle gourd juice can cause complications, while over 200 ml has proved to be fatal (Chandra, 2010). Cucurbitacins present in the juice results in gastrointestinal toxicity which causes abdominal pain, vomiting, diarrhea, hypotension and upper gastrointestinal bleed. Though toxic to animals, the bitter taste is said to deter humans from consuming large amounts, thus, prevents poisoning. Higher levels of these cucurbitacins are triggered by environmental stress, like wide temperature swings, low pH, high temperature, too little water, low soil fertility and improperly stored or over matured fruits (Chandra, 2010; Puri *et al.*, 2011; Sukhlecha, 2012). Therefore, it is important to have an appreciation of the ecology where bottle gourd is found before introducing it to new locations so as to avoid increasing the toxicity

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Ecology and productivity

As stated earlier, adaptation and distribution of bottle gourd is bi-hemisphere and therefore grows well within the tropical and temperate regions of Africa, Indo-Malaysia, the Americas and neo-tropics. Sillotoe (1983) and Grubben and Dento (2004) observed good adaptation in high elevated sub-tropical, tropical and temperate climates, as well as low-lying semi-arid to arid climates. Bottle gourd grows well in areas with rainfall of between 400 – 1 500 mm per annum; however, moderate, rather than excessive soil water is desired for good harvest (Haque *et al.*, 2009). Therefore, bottle gourd is intolerant of water logging. According to Grubben and Dento (2004), bottle gourd grows well under warm temperatures (25 – 35°C). Under frost–free, low temperature conditions it will also grow well provided the plants have attained sufficient vegetative growth before the onset of cool weather. Optimum germination temperature is between 20 and 25°C. Temperatures below 15°C and above 35°C reduce the germination rate (Sivaraj and Pandravada, 2005). This cucurbit has been observed to do well in a range of soils, which are fertile and well–aerated. Flowering is highly sensitive to

photoperiod. Short days, coupled with low night temperatures and high relative humidity, promote the development of male flowers, while the reverse promotes female flowers (Haque *et al*., 2009). Agronomic practices that promote the production of more female flowers than male flowers could increase yields; however, Haque *et al*. (2009) observed less seed set due to the reduction of pollen. It is, therefore, important to determine the optimum ration of male and female flowers to optimise fruit and seed set.

Not much information is available on the production of bottle gourd, especially in the southern African context where women are the main custodians of its husbandry. The FAO provides combined production data for pumpkin, squashes and gourds; as such there is difficulty in ascertaining the exact amount of global bottle gourd production. In Bangladesh, Haque et al. (2009) observed yields of 35 t/ha in sub-tropical to tropical conditions and less than 20 t/ha in semi–arid conditions. Hybrid varieties in Asia have recorded yields of more than 40 t/ha under optimum conditions, while local landrace varieties produced less than 25 t/ha. In view of changing climatic conditions, serious poverty and malnutrition, there is a need to unlock the potential of neglected underutilised species, through the generation of information on general crop husbandry.

As a way of understanding the amount of diversity for bottle gourd, different landrace selections need to be collected and stored in regional seed gene banks. This will allow genetic preservation and ease access for researchers. In the context of Africa, research is lacking on agronomic management of crop; fertiliser requirements, plant densities, planting dates and water requirements over different agro-ecological zones. Other areas of research that could be looked into include the efficiency of bottle gourd as live mulch for weed suppression; its water utilisation and effect of drought stress on growth, development and yield. It is also clear that there is a dearth in information on seed technology of bottle gourd.

The desire of any farmer is to see the germination and growth of all seeds planted in a field. This way the farmer is assured to obtain reasonable yield if all growing conditions are optimal. This is not always the case with resource limited farmers practicing agriculture in sub-optimum conditions while growing poor quality seed. According to numerous researches, the main source of plant material grown by resource limited farmers is seeds that have been saved from the previous season or exchanged. These sources of seed are often of inferior quality in terms of genetic purity and germination, leading to poor crop stands, lower yield and food insecurity. Although bottle gourd is an ancient crop, there is little information on its

seed quality. Since seed is important for crop establishment, it is important to study it as a major element of an underutilised species.

Seed quality

Seed quality has been described as a multiple concept comprising several components (De Geus *et al*., 2008; Powell *et al*., 1984; Thompson, 1979). Hampton (2002) described seed quality as the standard of excellence in certain characteristics that will determine seed performance when the seed is either stored or sown. According to De Geus *et al*. (2008) it is the physiological (seed germination ability and seed vigor) and genetic quality. Thomson (1976) included aspects of genetic purity, analytical purity (the absence of contaminants from foreign species and matter), pure seed, healthy seed (the absence of seed borne pathogens), correct moisture content and uniformity in mixing and blending of seed size. On the other hand, Burgrass and Powell (1984) stated that seeds with poor quality will show symptoms of typically aged seed such as low viability, reduced germination, poor emergence and seedling growth, and poor tolerance to suboptimum conditions. From all these components of seed quality, Odindo (2008) stated that germination capacity and physiological vigour are the two most important indicators of seed quality, because they are intrinsic properties of the seed.

The effect of different seed morphologies on seed quality has been studied; however, the main focus was seed poly-morphism (single plant produces two or more seed types with different morphology) and seed quality. There is a dearth of information on seed quality for different varieties belonging to the same sub-species possessing different seed forms such as bottle gourd. Seed morphology is determined both by seed genotype and parental environment (Lacey and Herr, 2000). Most quality characteristics of seeds have been described as polygenically inherited, and will, therefore, be influenced by the environment, to a large extent. For example, Ye et al. (2003) observed a genotype by environment interaction on seed quality of cotton, Krishnan and Suryarao (2005) in rice varieties, while Cowling and Tarr (2004) observed these differences in lupin. Adebisi and Ajala (2006) observed significant seed quality differences between different cultivars of sesame harvested from plants grown in diverse populations.

Seed quality of landraces/populations or open pollinated varieties (OPVs) has been shown to be of a lower standard than hybrid seed due to differences in genotype composition. Mabhaudhi and Modi (2010) observed better seed quality for hybrid than landrace varieties under optimum conditions, while the reverse was observed under sub-optimum conditions.

49

Wongvarodon and Naulkong (2006) observed better germination of Bambara landraces than hybrid seed when accelerated aging had been induced. Idikuta et al. (2012) observed better germination and vigor for popcorn landrace varieties when compared with hybrid seed under salt and high temperature conditions. Therefore, for a cross pollinated crop like *L. siceraria,* differences in seed quality can be expected between plants, fruits within the same plant and seeds at different positions within the fruit. While genetic makeup determines the base line potential of seed quality, other heritable factors, such as seed size have been found to have an equal role to play towards enhanced seed quality.

Theoretical considerations predict that large seeds will yield better and more competitive seedlings than smaller seed, hence high seed quality (Gross, 1984; Marshall, 1986; McGinley et al., 1987; Lehtila and Ehrlen, 2005; Pettigrew and Meredith, 2009). According to Soltani et al. (2002), the possible effect of seed size on seed quality (germination and vigour) is associated with the duration and the rapid provision of energy to the developing seedling. That is, there is a higher seed reserve utilisation rate in bigger seeds than small ones. Chastin et al. (1996) suggested that larger seeds produce seedlings with better early growth and increased competitive ability against weeds and pests. Amico et al. (1994) concluded that higher vigour that occurred in larger seeds was due to the larger food reserves in these seeds. They also noted a positive linear relationship between seed mass and emergence in the field. Baalbaki and Copeland (1997) reported that in wheat, seed size not only influenced emergence and establishment but also affected yield components and ultimately grain yield. A similar observation was made by Arunachalam et al. (2003), while working with the tree species, and this was attributed to the larger food reserves in the larger seeds. Also, these results indicated that seed size had greater effect on percent than index of germination and emergence. With increased seed size, higher germination and emergence were determined in triticale (Kayden and Yagmur, 2008), but besides higher germination percentage declined median germination time were determined in some forage plants (Larsen and Andreasen, 2004). In another study, Willenborg et al. (2005) stated that germination was increased with increasing seed size in oats (Avena sativa L.). In pea (Pisum sativum L.) cultivars with low 100 seed weight had higher germination percentage than larger seed ones (PekÕen et al., 2004).

Seed size is considered as one of the least plastic traits of seed morphology (Gross, 1984), and according to Hossain et al (2010) its heritability varies for different species. For example, the heritability in Medicago sativa was 0.14, while Hevea brasiliensis had 0.90. Mendez (1997) observed variation in seed size and quality between and within plant species, within

plants for inflorescences produced at different growth stages, and for seeds developing at different positions within the fruit. According to Vaughton and Ramsey (1997), such evidence is contrary to the theoretical concept that the mother plant will partition all resources equally to developing seed. Causes of variation could be due to the relative position of the fruit (Mendez, 1997), differences in nutrient supply by mother plant to developing seeds, often related to genetic quality of the seed (PekÕen et al., 2004), parental/sibling conflict and sibling rivalry (Benuelos and Obeso, 2003) and parent fitness (Leishman, 2001). Creating trade-offs between seed size and seed number (Gross, 1984; Venable, 1992; Jakobsson and Eriksson, 2000).

Seed is a key input in crop production. All cultural practices are designed to exploit the full genetic and physical potential of seeds sown. No agricultural practices (for example tillage, cultivation, weeding, fertiliser, pest and disease control) can increase crop yields beyond the limit set by the seed quality. Seed is therefore the baseline for success or failure of the crop planted. To increase available information on bottle gourd and to translate effective breeding programs and agronomic practices, it is necessary to obtain information on seed morphology as it may affect seed quality (Morimoto *et al*. 2005; Costa *et al*. 2011). This section sort to address the second half of the objective which was to evaluate the magnitude of variation in seed morphology of different bottle gourd landrace selections and its effect on seed quality on the basis of germination, vigour and EC.

MATERIAL AND METHODS

Plant material

Six mature fruit of bottle gourd landraces were randomly (without any order or design) collected from farmers' fields in Richards Bay (28°19'S; 32°06E; 30 m above sea level (masl)), in northern KwaZulu-Natal, South Africa and Chimbwanda East (18°19'S; 31°12'E; 1484 masl), in Mashonaland East province, Zimbabwe. Before the experiment, seeds were extracted from each fruit and surface sterilised by immersing them in a 5% solution of sporekill for 5 minutes. Seeds were then dried at room temperature (21 to 28ºC) for 24 hours. Table 1 gives a brief description of the landrace selections and agro-ecological characteristics of where they were collected while Fig. 2 is a picture of seeds for the different landrace selections.

Table 1 Description of the bottle gourd landraces and agro-ecological characteristics of where they were collected

Landrace	Fruit shape	Shell texture	Fruit length (cm)	Location	Climate
CAL	Calabash	Smooth	45.6	Richards Bay	Sub-tropical
ZIM 1	Oval	Smooth	29.85	Chimbwanda east	Semi-arid
ZIM 2	Spherical	Warted	26.96	Chimbwanda east	Semi-arid
S	Pumpkin shaped	Smooth	9.49	Richards Bay	Sub-tropical
C	Club shaped	Warted	24.97	Richards Bay	Sub-tropical
R	Spherical	Smooth	11.55	Richards Bay	Sub-tropical

2.2 Experimental design and data collection

All experiments where laid out in a randomised complete block design with three replicates at the University of KwaZulu-Natal's (UKZN) seed technology laboratory. The number of seeds used per replicate varied for each experiment. Details of each experiment are given below.

Seed morphology

Ten seeds of each landrace selection were randomly selected and the following quantitative morphological parameters were determined: seed length (SL), width (SW), size (SZ = SL x SW), mass (SM), seed coat mass (SCM), seed coat thickness (SCT), embryo length (EL), embryo width (EW), embryo size (EZ = EL x EW), and embryo dry mass (EDM). Seed and embryo lengths and widths were measured using a digital vernier calliper (VT Zero (limited), while mass was measured using a digital scale. Seed coat thickness was determined using a Zeiss EVO scanning electron microscope (SEM) in a vapour pressure mode (Chakrabarti *et al*. 2003).
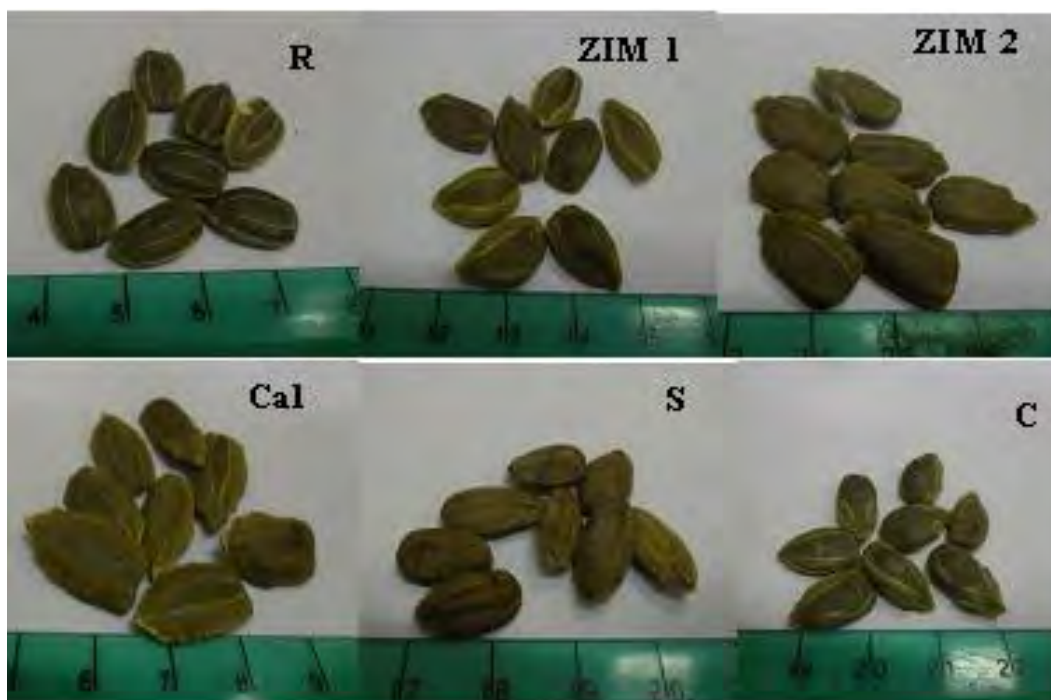
Fig. 2. Pictures of seeds for the different landrace selections (ZIM1, ZIM2, R, S, C and CAL).

Lignin was determined using the modified acetyl bromide procedure of Liyama and Wallis (1988) except that three replicates of 20 mg samples each were weighed into 4-ml brown vials and 2.0 ml of 25% acetyl bromide containing perchloric acid (70%, 0.08 ml) was added. After digestion, the samples were dissolved in acetic acid and then transferred to 50 ml volumetric flasks containing 2M sodium hydroxide (5 ml) and acetic acid (12 ml). The flasks were made to the mark with acetic acid.

Seed quality test

For the standard germination test, three replications of 20 seeds per replicate were germinated between double layered moistened paper towels (ISTA, 2003) in an illuminated germination chamber set at 20°C/30°C (16 hours day/ 8 hours night) for 14 days (AOSA, 1992). Germination counts were taken daily, with radicle protrusion being the criterion used to indicate germination. Final germination count was based on visual observation of normal seedlings according AOSA (1992) guidelines. On day 14, root and shoot lengths, root: shoot ratio and seedling fresh mass were measured. Fungi infection was visually scored with 1

representing no infection and 5 representing heavily infested. Germination velocity index (GVI), was calculated based on a formula by Maguire (1962):

$$GVI = G_1 N_1 + G_2 N_2 + \ldots\ldots + G_n N_n$$

Where: G_n is the number of germinated seeds in count n

               N_n is the number of sowing days at n count.

Seed electrical conductivity was determined using three replicates of initially weighed 20 seeds per treatment following imbibition in 100 ml of de-ionized water at 25°C for 24 hours. Following this, electrical conductivity (EC) was measured using an EC meter (Hanna H1 991300).

Imbibition was done on a seed testing water bath (Grant Instruments, England). Ten seeds per landrace selection were placed in a completely randomised design experiment with three replicates per selection. Seeds were imbibed for 0, 15, 30, 60, 120, 240, 720, 840, 960, 1440, 2160, 2880, 4320, 5760 and 7200 minutes and the percentage change in seed mass during imbibition was measured at each time interval.

Data analysis

All data were subjected to analysis of variance (ANOVA) using GenStat® (Version 14, VSN International, UK). Means of significantly different variables were separated using least significant differences (LSD) at a probability level of 0.05. Data on morphological traits were then subjected to principal component analysis to establish traits that contributed to seed variation. Raw data were standardised to give a mean of zero and a standard deviation of +/- 1. This was followed by computing and construction distance matrix using variance-covariance coefficients. Eigen values and eigen vectors of the variance-covariance matrix were then computed to generate PC1 and PC2 scores. The landrace selections were then plotted on a bi-plot using the first two principal component scores (PC1 and PC2). Correlation analysis was done on selected variables to establish relationships.

RESULTS

Seed morphology

Seed and embryo length

Significant differences (P<0.001) were observed across the landrace selections for both seed and embryo length (Fig. 3). Landrace selection CAL had the longest seed length and this was followed by ZIM 2. The shortest landrace selections were R, C and S, respectively. A similar trend of length was observed in embryo length (Fig. 3).
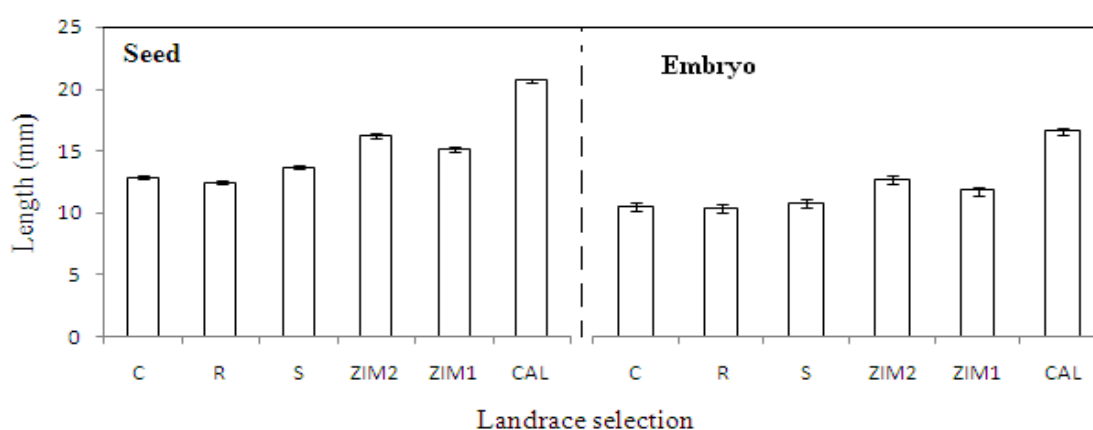
Fig. 3. Seed and embryo length of selected bottle gourd landrace selections (ZIM1, ZIM2, R, S, C and CAL). Landrace selections significantly different from each other for seed and embryo width at P < 0.001; Mean values ± Standard error of means of six landrace selections.

3.1.2 Seed and embryo width

Highly significant ($P < .001$) and significant ($P = .04$) differences were observed among the landrace selections for seed width and embryo width, respectively (Fig.4). Landrace selection CAL had the widest seeds and this was followed by R, ZIM 1 and ZIM 2; and these were not significantly different from each other (Fig.4). The narrowest seeds belonged to landrace selection R. Similar to seed width landrace selection CAL had the widest embryo. Landrace selection ZIM 1 had the narrowest embryo and its width was not significantly different from those of ZIM 2, R, C and S.

55
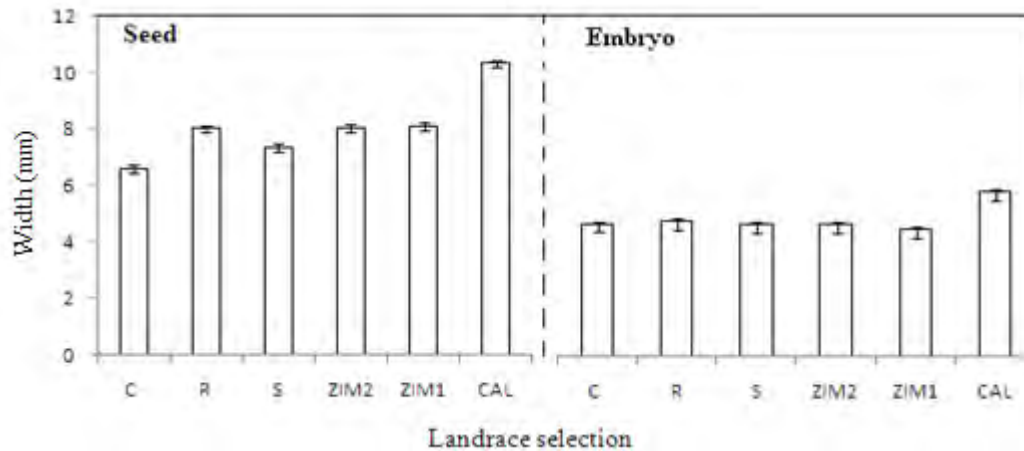
Fig. 4. Seed and embryo width of selected bottle gourd landrace selections (ZIM1, ZIM2, R, S, C and CAL). Landrace selections significantly different from each other for seed and embryo width at P < 0.001 and P < 0.05, respectively; Mean values ± Standard error of means of six landrace selections.

3.1.3 Seed and embryo size

There were highly significant ($P < .001$) and significant ($P = .02$) differences observed across the landrace selections for seed size and embryo size, respectively (Fig.5). High standard deviation was also observed for the landrace selection for seed and embryo size (46.23 and 22.36, respectively). As expected, landrace selection CAL had the largest seed size and it was followed by ZIM 2. The landrace selection with the smallest seed size was C (Fig.5). Landrace selection CAL also had the largest embryo size and this was also followed by ZIM 2. There were no significant differences of embryo size between landrace selections C, R, S and ZIM 1 (Fig.5) while significant differences were observed for ZIM 2 and CAL.
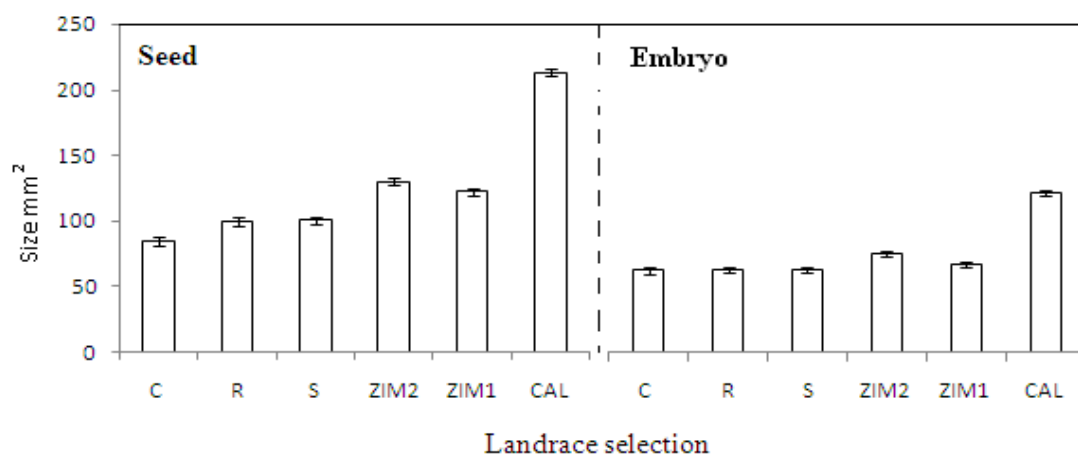
Fig. 5. Seed and embryo size of selected bottle gourd landrace selections (ZIM1, ZIM2, R, S, C and CAL). Landrace selections significantly different from each other for seed size at P < 0.05; Mean values ± Standard error of means of six landrace selections.

3.1.4 Seed, embryo and seed coat weight

Significant differences ($P = 0.03$) were observed among the landrace selections for seed, embryo and seed coat weight (Fig.6). Results of the analysis showed that landrace selection CAL had the heaviest seeds while there were no significant differences in seed mass for the other landrace selections. Similarly, CAL had the heaviest seed coat but it showed no significant difference with selections ZIM 1 and C. What was interesting to note was that the embryo mass of landrace selection R was similar to that of CAL, although it had the lightest seed coat and had the smallest embryo size.
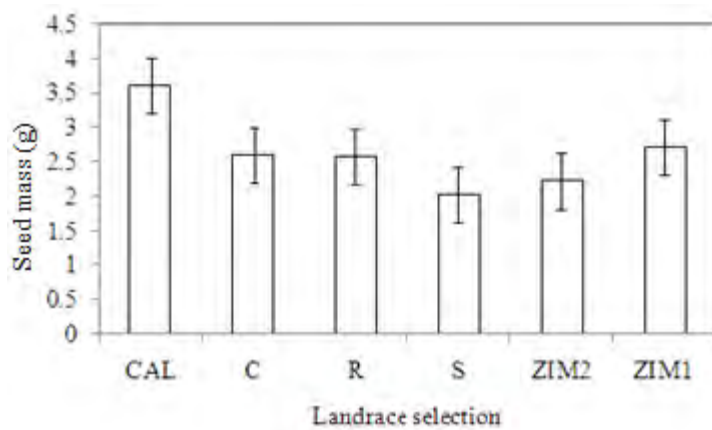
Fig. 6. Landrace selections significantly different from each other for seed mass at P < 0.05; Mean values ± Standard error of means of six landrace selections.

The proportion of seed coat mass contributing towards total seed weight differed for some landrace selections while it was somewhat constant in others (Fig.7). Seed coat for landrace selection R contributed 53% towards total seed mass, while 47% was contributed by the embryo. Seed coats of landrace selections C, ZIM 2, CAL and S contributed lightly towards the total seed mass with 30%, 33%, 35% and 37%, respectively, while embryos contributed 70%, 67%, 65% and 63%, respectively (Fig.7).
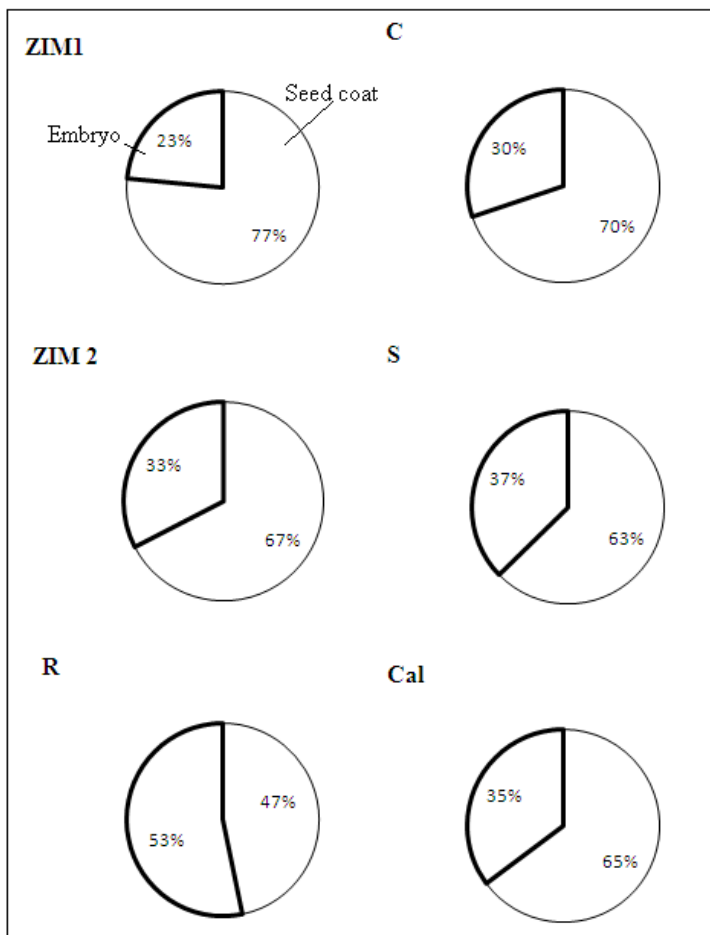
Fig. 7. Percentage contributions of seed coat and embryo mass to total seed mass for six bottle gourd landraces (ZIM1, ZIM2, R, S, C and CAL).

3.1.5 Seed coat thickness

Highly significant differences ($P < .001$) were observed among the selections for seed coat thickness (Fig.8). High standard deviation of 39.88 was also observed for seed coat thickness across the landraces. Landraces with the thickest seed coats were Zimbabwean selections ZIM 1 and ZIM 2 (Fig.8). And these selections were not significantly different from each other. Landrace selections with the thinnest seed coats were S and C and these were not significantly different from the other South African landrace selections.
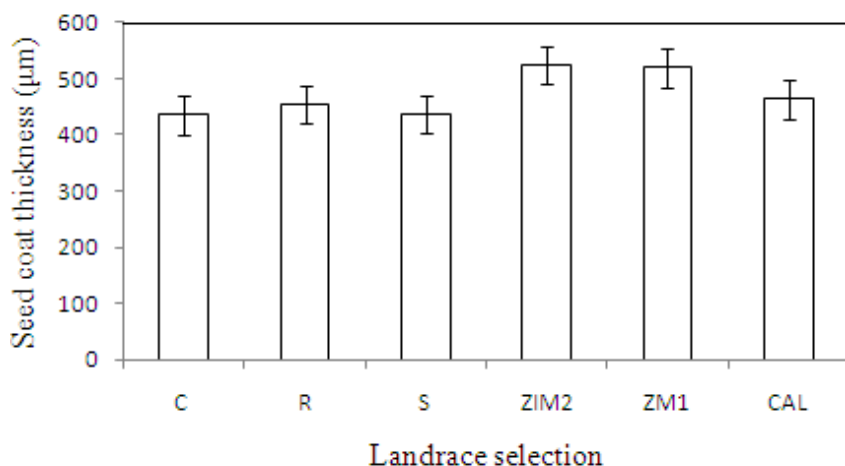
Fig. 8. Seed coat thickness of selected bottle gourd landrace selections (ZIM1, ZIM2, R, S, C and CAL). Landrace selections significantly different from each other for seed coat thickness at P < 0.001; Mean values ± Standard error of means of six landrace selections.

3.1.6 Total fibre content in seed coat

Significant differences ($P = .03$) for total fibre content were observed among landrace selections (Fig.9). Results show that landrace selection C had the least amount of fibre in their seed coats and selection S had the most (Fig.9).
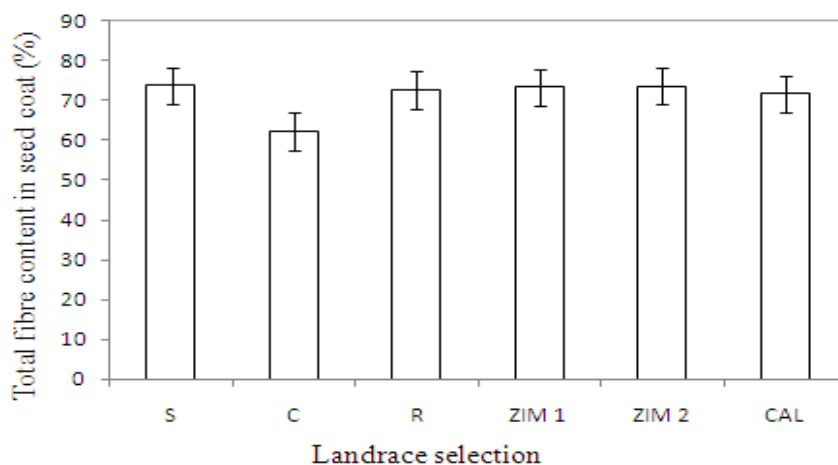
Fig. 9. Total fibre content in seed coats of selected bottle gourd landrace selections (ZIM1, ZIM2, R, S, C and CAL). Landrace selections significantly different from each other for total fibre content in seed coat at P < 0.05; Mean values ± Standard error of means of six landrace selections.

60

3.1.7 Principal component analysis

Results of the principal component analysis for the 10 morphological traits indicated that the first two PCs explained 98.64% (PC 1: 65.68% and PC 2: 34.16) of the variation among the landrace selections. Seed size had the largest contribution to PC 1 and this was followed by EZ and SCTH. On the other hand, SCTH had the largest contribution to PC 2 and this was followed by SZ and EZ (Table 3).
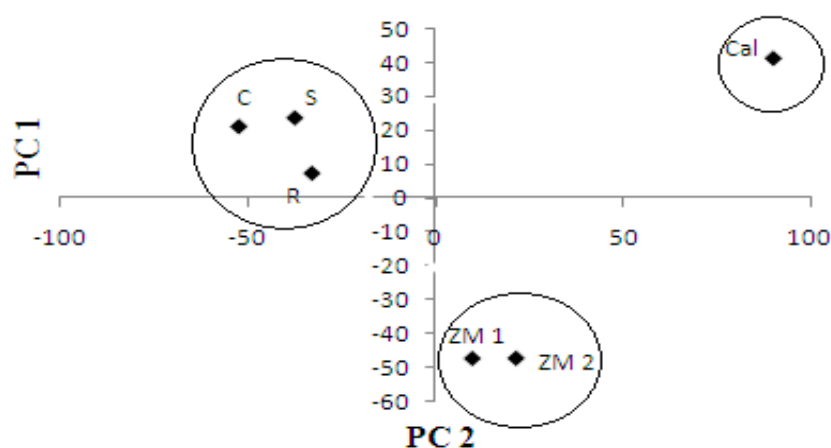
Table 3. **The first two principal component scores of 10 measured traits on six landrace selections of bottle gourd (ZIM1, ZIM2, R, S, C and CAL).**

TRAIT	PC1	PC1
EL[1] (mm)	0.046	0.013
EW (mm)	0.008	0.009
EZ	0.390	0.223
EDM (g)	0.003	0.004
SL (mm)	0.056	0.011
SW (mm)	0.022	0.006
SZ	0.855	0.263
SWT (g)	0.008	0.006
SCTH (μm)	0.333	-0.939
SCM (g)	0.007	0.001

[1] Embryo length (EL), embryo width (EW), embryo size (EZ = EL x EW), embryo dry mass (EDM), seed length (SL), width (SW), size (SZ = SL x SW), mass (SM), seed coat mass (SCM) and seed coat thickness (SCTH).

Fig.10 shows principal component (PC) analysis plot of first two principal components depicting relationships among bottle gourd landrace selections. The selections were separated into 3 distinct groups. In a clockwise direction, the first cluster was a single landrace selection group which consisted of CAL. The following cluster comprised of the two Zimbabwean

selections (ZIM 1 and ZIM 2) while the final cluster had the three local landraces (C, R and S) (Fig.10).

Fig. 10. Principal component (PC) analysis plot of first two principal components depicting relationship among bottle gourd landrace selections (ZIM1, ZIM2, R, S, C and CAL).

Looking at the trait that contributed to seed variation, according to PC 1 and PC 2 at a cluster level, it is evident that the first cluster had thinner seed coats and had smaller seed and embryo (Fig.10). The second cluster comprised of landrace selections with the thickest seed coats, but had moderately larger seed and embryos than those in the first cluster (Table 4). The landrace selection in the third cluster also had a thinner seed coat, though thicker than the first cluster, but had the largest seed and embryo sizes (Table 4).

Table 4. Characteristics of landrace selection cluster groups based on morphological traits that contributed much variation to seed.

|	Clusters		
Trait	**1**	**2**	**3**
SCTH[2] (μm)	442.22	521.84	463.53
SZ (g)	95.11	126.43	213.36
EZ (g)	60.20	68.04	116.86

[2]SCTH – seed coat thickness, SZ – seed size, EZ – embryo size.

Seed quality

Seed germination

Although data was not subjected to any statistical analysis, germination percentage was different across the different landraces. Germination of landrace selections started on the fifth day of incubation with large number of seeds germinating for landrace selection C and ZIM 2 (Fig.11). Seeds continued to germinate steadily until they reached their peak of 84% on day 12. For R, CAL and ZIM 1, fewer seeds germinated on day 5 and the maximum numbers of germinated seeds were recorded on day 10 for landrace selection R, day 11 for S and day 12 for ZIM 1 and CAL (Fig.11).
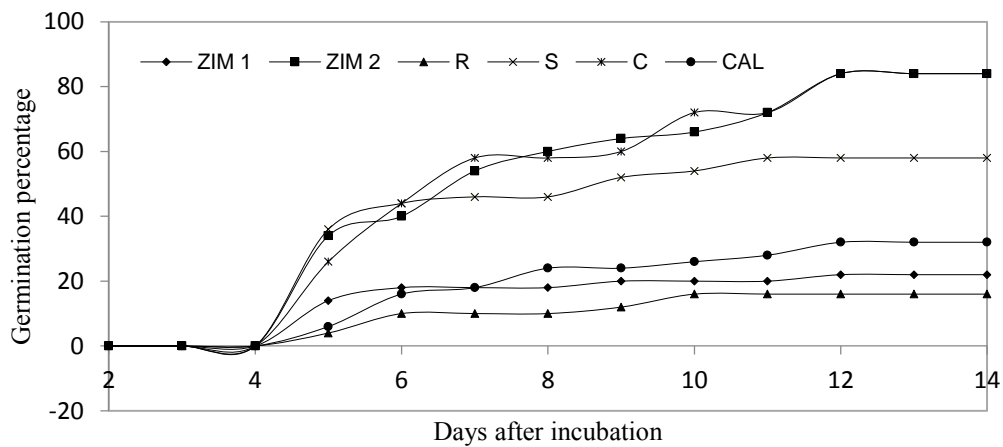
Fig. 11. Progress in daily germination percentages of landrace selections (ZIM1, ZIM2, R, S, C and CAL). (ZIM1, ZIM2, R, S, C and CAL) during the first 14 days.

3.2.2 Electrical conductivity

There were significant differences ($P = .03$) observed for EC across the landrace selections. High EC values were observed for landrace selection R and this was followed by ZIM 2. CAL had the least EC and this was not significantly different from those of ZIM 1, S and C (Fig.12).

3.2.3 Fungi scores

There were significant differences (P = .05) observed for fungi score across the landrace selections. High fungi scores were observed for CAL, ZIM 1 and R while ZIM 2, S and C had low fungi scores (Fig.12).

3.2.4 Germination velocity index

There were significant differences ($P = .03$) observed for GVI across the landrace selections. Results showed that CAL and ZIM 1 had the lowest GVI. The rest of the landrace selections had higher GVI and these were not significantly different from each other (Fig.12).

3.2.5 Seedling dry mass

There were significant differences ($P = .05$) observed for seedling dry mass across the landrace selections. Results showed that landrace selection CAL had the heaviest seedling dry mass. Landrace selection C had the lowest seedling dry mass and it was not significantly different from R and S.
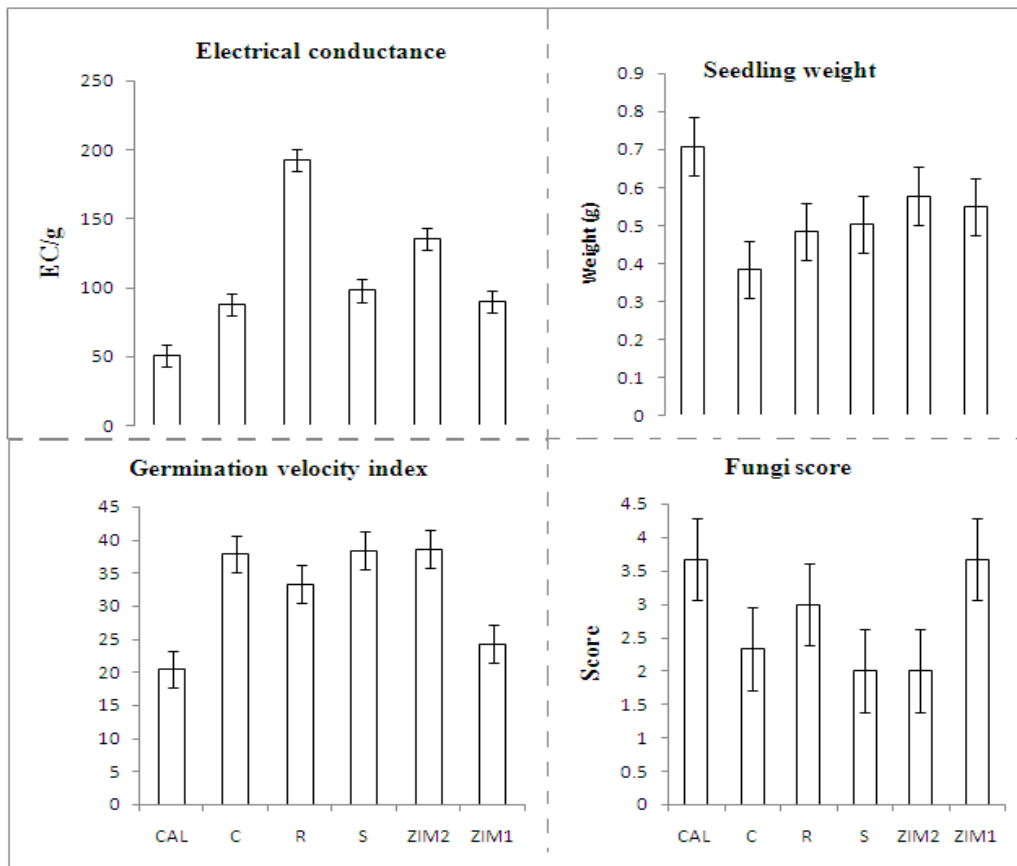
Fig. 12. Electrical conductivity, seedling mass, germination velocity index and fungi scores of different landrace selections (ZIM1, ZIM2, R, S, C and CAL).   Mean values ± Standard error of means of means of six landrace selections.

3.2.6 Seed imbibition

Results of the imbibition experiment showed that the rate of imbibition differed across landrace selections and at different times measured (Fig.13). The rate of imbibition for landrace selections R and S was higher than the other varieties as explained by the largest seed mass increment at the shortest time. Landrace selections S, ZIM 1, ZIM 2, and CAL had somewhat the same imbibition rates from the beginning of the experiment till 7200 minutes (Fig.13). What was interesting to note was that landrace selection C actually lost mass at two time intervals (15 and 60 minutes of imbibition). Similarly, CAL lost seed mass 960 minutes into the experiment of which it there afterwards (Fig.13).
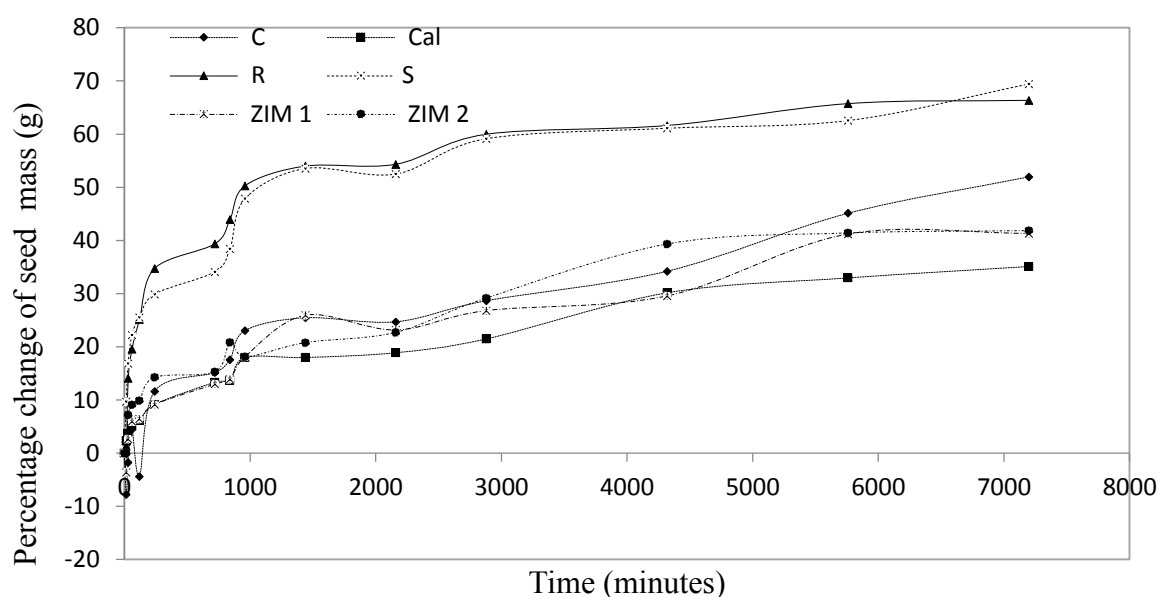
Fig. 13. Percentage change in seed mass of imbibed landrace selections (ZIM1, ZIM2, R, S, C and CAL). Percentage change of seed mass was recorded at 15, 30, 60, 120, 240, 720, 840, 960, 1440, 2160, 2880, 4320, 5760 and 7200 minutes after incubation on a water bath table.

Correlations among morphological traits and seed quality indices

Positive and significant correlations were observed for most seed morphological traits. Embryo length (EL) was positive and significant correlations with embryo width (EW) (r = 0.872, *P = .02*), embryo size (EZ) (r = 0.980, *P = .001*), seedling mass (r = 0.920, *P = .012*), seed length (SL) (r = 0.993, *P < .001*), seed width (SW) (r = 0.914, *P = .013*), seed size (SZ) (r = 0.990, *P < .001*). Embryo width had positive and significant correlations with EZ (r = 0.951, *P = .011*), SL (r = 0.818, *P = .012*), SW (r = 0.844, *P = .011*), seed mass (SWT) (r = 0.834, *P = .012*) and SZ (r = 0.880, *P = .012*). Embryo size had significant and positive correlations with SL (r = 0.955, *P < .001*), SW (r = 0.915, *P < .001*) and SZ (r = 0.978, *P < .001*).

A negative but significant correlation was observed between embryo mass and root length (r = -0.850, *P = .04*). Embryo size had a positive and significant correlation with seedling mean mass (SDLWT). Although fungal infection was not an experimental treatment, observations showed that it had a negative and significant effect on germination (GERM %) (r

= -0.819, *P* = *.04*), germination velocity index (GVI) (r = -0.953, *P* = *.012*), SWT (r = -0.811, *P* = *.013*) and shoot length (r = -0.877, *P* = *.02*). Seed mass was positive and significantly correlated with GERM% (r = 0.939, *P* < *.013*) but was negatively correlated with GVI (r = -0.863, *P* = *.03*). On the other hand, GVI had a negative and significant correlation with seed coat mean mass (SCWT) (r = -0.875, *P* = *.014*) and a positive and significant correlation with shoot length (r = 0.881, *P* < *.001*). Shoot length was positive and significantly correlated to root length (r = 0.0842, *P* = *.012*); but it was negatively correlated to seed mass (r = -0.990, *P* < *.001*). Seed size was positive and significantly correlated with SDLWT (r = 0.948, *P* = *.013*). Imbibition was significant and negatively correlated to seed coat thickness (r = -0.650, *P* = *.04*) and seed germination (r = -0.500, *P* = *.05*). On the other hand, imbibition had a significant positive correlation to total fibre content of seed coats (r = 0.63, *P* < *.04*) and EC (r = 0.643, *P* = *.04*).

DISCUSSION

Morphological characterisation has been used by many scientists as a method of distinguishing differences among plant species populations. Knowledge of existing variation and associations between various morphological traits is vital for many evaluation experiments as it allows the identification of superior performing genotypes (Morimoto *et al.* 2005; Costa *et al.* 2011). Based on results obtained in this study, seed for landrace bottle gourd selections portrayed a wide range of diversity in terms of the quantitative traits measured. These results are similar to those obtained by Decker-Walters (2001), Yetişir *et al.* (2008) and Morimito *et al.* (2005) who observed large variation in seed morphology across different bottle gourd landrace selections.

Based on traits contributing most to seed variation, the observed results for standard deviation corresponded well with those of principal component analysis, which lead to the clustering of the landrace selections by provenance and seed size. The observed results on seed coat thickness are similar to those observed by Nooden et al. (1985) in soybean, who associated seed coat thickening with adaptation strategies to stress conditions such as moisture and heat. Seeds obtained from Zimbabwe were produced in semi-arid conditions whereas those obtained in Richards Bay were from a more sub-tropical climate. On the other hand, it was observed that thicker seed coat had negative effect on root: shoot ratio. According to Bewley (1997) thick seed coats can act as a barrier against radicle protrusion. Radicles will therefore, take longer to emerge from the seed coat thence appearing shorter and

reducing root: shoot ratio. During periods of low soil moisture, reduced root: shoot ratio can have a negative effect on seedling establishment since few roots occupy a smaller volume of soil, thus extracting less water. Such landrace selections can succumb more to the negative effect of drought and produce poor quality seedlings. This would suggest that thinner seed coats are more desirable for farmers practicing agriculture in water limited environments wanting faster and more uniform germination since seeds can quickly develop radicles that will absorb water faster before it is lost through negative water fluxes (drainage and evaporation).

Still on seed coat, the observed relationship between this trait and EC was similar to that observed by Borji et al. (2007) who showed the positive interaction between the two variables. Borji et al. (2007) demonstrated that an increase in seed coat thickness resulted in an increase in the availability of physiochemicals (water soluble compounds) within the seed coat that play an important role in the seed and its integrity when soaked in water. Therefore, seeds with thicker seed coats exude more physiochemicals thus giving off a high EC value. However, contrary to norm, EC was not a good indicator of seed quality. This could suggest that, for seed with thick seed coats, EC should always be accompanied by other seed quality tests to determine overall quality.

The observed differences in imbibition rates is similar to results obtained by Asiedu et al. (2000) who observed different rates in different soybean selections. According to Borji et al, (2007) the rate of water uptake is proportional to the diffusivity of water, which is determined by factors such as chemical composition, microstructure, moisture and temperature of the seed. Seed coat fibre, namely lignin has been found to affect permeability of seed; therefore, acting as a physical barrier affecting imbibition rate. The observed interactions between imbibition rate and seed coat fibre were also observed by Asiedu et al. (2000) and Sousa and Fihlo (2002). This could imply that seed treatments such as scarification with acid or abrasion could assist in increasing water absorption. On the other hand, other factors that should also be considered as factors that could have had an effect on imbibition are temperature of seed and water, pore size, density and distribution, seed coat colour, solute concentration and initial moisture content of the seed, which have all been found to be positively correlated with imbibition.

The observed changes in seed mass during imbibition are similar to those observed by Alencar et al. (2012) who observed its decline in Cereus jamacaru D.C. ssp. jamacaru (Cactaceae). According to Doman et al. (1982), cotyledons of most epigeic seedlings

differentiate into photosynthetic organs after the hydrolysis and mobilisation of stored reserves. During this time of hydrolysis and mobilisation the seed still gets its energy. This has been shown to result in a reduction of total embryo mass but not necessarily size. If seed reserves in the cotyledons are utilised at a faster rate than the rate of differentiation into photosynthetic organs, seeds could die before germination. With regards to bottle gourd, its embryo is rich in lipids and nitrogenous compounds. According to Alencar et al. (2012), lipids were the main reserve mobilised during germination because their levels were strongly reduced after seed germination, while proteins were the second most utilised reserve in this process. It would be interesting to establish the changes of biochemical composition of bottle gourd embryo in relation to the developing embryo in the seed axis.

Similar to observations by Nik et al. (2011), obtained results in this study showed that large seeds had large embryos. According to Gracia et al. (2003) seed size is primarily controlled by embryo size. On the other hand, the large contribution of seed coat mass towards the final seed mass of landrace selection R was similar to results obtained by Nazirul et al. (2009) who observed differences in embryo mass for different varieties of coconut seeds with the same size. Seeds of landrace selections like R could be very misleading for resource poor farmers that extract oil and use the defatted seed cake as a protein supplement. This is because embryo mass and seed oil content have been found to be significantly positively correlated (Marinkovic, 1992). Therefore, landrace selections like R could produce less oil and protein supplement per kilogram harvested.

Similar to results obtained by Akita et al. (1986) heavy seeds did not always mean high plant growth rates (root length). Nevertheless, the observed relationship between seed size and seedling dry mass could be due to the longer duration and the rapid provision of energy to the developing seedling provided by larger seeds (Soltani et al., 2002). Maree (1998) stated that the potential of seedling growth is a function of genetics since seed size is genetically controlled.

The obtained results between seed mass and GVI are contrary to those obtained by Kanmegne *et al.* (2010) who observed a positive correlation between the two traits. The lower GVI could be attributed to the high fungal infection observed on seed at day 14 of the experiment. This could be substantiated further with the observed interaction between germination percentage and fungal infection. According to Nik *et al*. (2011), fungi can inhibit seed germination and cause death of emerged seedlings by suffocating seed nutrients required for seed germination and growth.

CONCLUSIONS

Seed morphology of the different landrace selections was indeed different. Seed and embryo size and seed coat thickness contributed most to seed diversity. The local landrace selections had either large or small seeds, and all had thin seed coats. On the other hand, seeds of landrace selections from Zimbabwe were medium in size and had thicker seed coats when compared to the local selections. The germination percentage and EC of bottle gourd varieties were different and there were no correlations with most seed morphological traits. Seed size was correlated with seed quality as determined by seed germination rate and seedling quality. Therefore, in this study most measured traits were not good indicators of seed quality. Although, fungus was not a treatment, it had a negative effect on seed germination and vigour. Seed coat thickness may be used as a parameter for recommending varieties into different agro-ecological areas which warrants further investigation. Furthermore, aspects of seed dormancy and seed physiology and their effect on seed quality need to be established. It should be noted that, weaknesses to the study were the number of landrace selections and seeds used per landrace selection. As a future direction, more landrace selections and seeds should be used to increase the accuracy of the study.

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CHAPTER 4

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

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ABSTRACT

Water is the main factor affecting crop production in sub-Saharan Africa. It was hypothesized that intercropping sorghum (S) with either cowpea (C) or bottle gourd (B) would result in better productivity and water use efficiency (WUE). This was evaluated using a split–plot arrangement with sub–plots nested in a randomised complete block design within the main plot, replicated thrice. Water regimes [full irrigation (FI), deficit irrigation (DI) and rainfed (RF)] were allocated to the main plots. Sub–plots comprised intercrop combinations, SS (sole), C (sole), B (sole), SC (intercrop) and SB (intercrop). Data collected included soil water content (SWC), plant height (PH) / vine length, leaf number (LN), tillering (T) / branching, leaf area index (LAI), relative leaf water content (RWC), stomatal conductance (g_s) and chlorophyll content index (CCI) as well as biomass accumulation and partitioning. Yield and yield components, water use (WU) and grain water use efficiency (WUE_g)were calculated at harvest. Land equivalent ratio (LER) was used to evaluate productivity of the intercrop. Sorghum canopy size decreased ($P < 0.05$) (-6.7%, -10.6%, -89% and -79% for PH, LN, T and LAI, respectively) with decreasing water availability. Sorghum growth and development were unaffected by intercropping. Intercropping sorghum with cowpea improved g_s (23%) and CCI (6.56%) of sorghum under low water availability. Productivity of sorghum across varying water regimes and cropping systems was stable with final biomass, yield and HI of 2.4 t ha^{-1}, 0.98 t ha^{-1} and 35%, respectively. Overall, LER showed a 46% increase in productivity across all intercrop systems. Intercropping marginally increased WU (5.64%). Improvements of WUE were observed under SC and SB (54.65% and 46.98%, respectively) relative to SS. Intercropping sorghum with cowpea is recommended for semi– and arid environments since it promoted efficient use of water.

Keywords: land equivalent ratio; resource use; water use efficiency; yield

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 ($\approx$ 90%) is resource constrained, subsistence based and done under rainfed 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 bio–physical 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 instance, 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 minimized 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 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. It is possible that intercropping sorghum with either cowpea or bottle gourd can improve water management in rainfed 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.

Material and methods

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.

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 (2012/13 and 2013/14). 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 1). Soil physical properties have been shown to affect movement and availability of soil water for plants. The soil water characteristics (texture, 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}) hydraulic conductivity (mm hr^{-1}) were determined using hydraulic properties calculator (http://hydrolab.arsusda.gov/soilwater/Index.htm) for each depth (Table 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 1: Soil water properties at different depths for soil at the experimental site.

Depth (m)	Texture	BD[1]	HC[2]	PWP[3]	FC[4]	TAW[5]	SAT[6]	K_{SAT}[7]
Units		(g m^{-3})	---------------------------(mm m^{-1})---------------------------					
0 – 0.10	Clay loam	1,29	0,34	21,04	33,54	12,5	48,66	20,9
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	1,4	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.

Experimental design and layout

The experimental design was a split–plot design arrangement with sub–plots arranged nested in a randomised complete block manner design within the main plot 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, 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 initiations and reinstated upon appearance of the flag leaf. Before planting and up to crop establishment, soil were irrigated to maintain 80% field capacity so as 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):

$$ET_c = ET_o * K_c \qquad \text{Equation 1}$$

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. This gave a population of 7168.5 and 4848.5 plants ha^{-1}.

Data collection

Climate data*:* Daily weather data were obtained from an 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 and placed in a plastic zip–lock bag and kept in a cool place for two hours. Thereafter, three disks each measuring 0.5 cm in diameter were cut out and immediately weighed so as 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:

$$RWC\% = \frac{FM-DM}{TM-DM} \ X \ 100\%$$
Equation 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 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):

$$GDD = \left[\frac{T_{max} + T_{min}}{2}\right] - T_{base}$$ Equation 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 (Clerget et al 2008).

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 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 glass house 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 glass house for drying and to hasten drying process of fruits they were cracked open. Fruit 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:

$$HI = \frac{Yg}{B}$$
Equation 6

where: HI = harvest index (%),

       Yg = 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 total of each component HI.

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

WU = P + I – D – R – ΔSWC
Equation 7

where: WU = water use = 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 5%. Drainage was also considered as 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 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 six (0.10 – 0.60). Due to nominal 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. 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:

$$\Delta WU \ (\%) = \left[\left(\frac{WU_{ic}}{P_a WU_{sa} + P_b WU_{sb}} \right) - 1 \right] * 100\% \qquad \text{Equation 8}$$

where: WU_{ic}, WU_{sa} and WU_{sb} = the water use in intercropping, sole cropping species A and sole cropping species B, respectively, and

P_a and P_b are the proportions of species A and B in the intercrop, given by P_a = $D_a/(D_a + D_b)$ with D_a and D_b 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:

$$WUE_{Y\ or\ B} = \frac{Y\ or\ B}{WU}\ (kg\ mm^{-1}\ ha^{-1})$$

Equation 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 (1993a) was used:

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

Equation 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 to be higher in the intercrop system relative to the sole crop.

Agronomic practices

Prior to planting, soil samples were obtained from the field trial site and submitted 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.

Statistical analyses

Data was combined after a homogeneity test of variance using the Bartlett's test. The test showed heterogeneity of variance 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.

Results

Weather data

Weather data for the two growing periods was consistent with long term weather data for Ukulinga (Section 2.2). 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 1). Although maximum temperatures for both growing seasons were similar (25.4 and 26.0°C for 2013/14 and 2014/15, respectively), minimum temperature in 2014/15 (16.6°C) was 2.4°C higher than the observed temperature during 2013/14 (19.0°C). Maximum and minimum temperatures were consistent with long term temperature averages of 25.63 and 16.89°C during the growing seasons. This resulted in a high rate for 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 where no rain was recorded in 2013/14 (105 days) than 2014/15 (49 days) (Fig 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 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 hail storms were more frequent during 2014/15 (6th and 13th February, 2015) season than during 2013/14 (21st February, 2014) (Fig 1). During 2014/15, hail storms coincided with the late vegetative stage hence making plants more susceptible to defoliation compared to during 2013/14 when plants were at the early vegetative stage and suffered relatively less defoliation. With each incident there was substantial loss in plant canopy size.
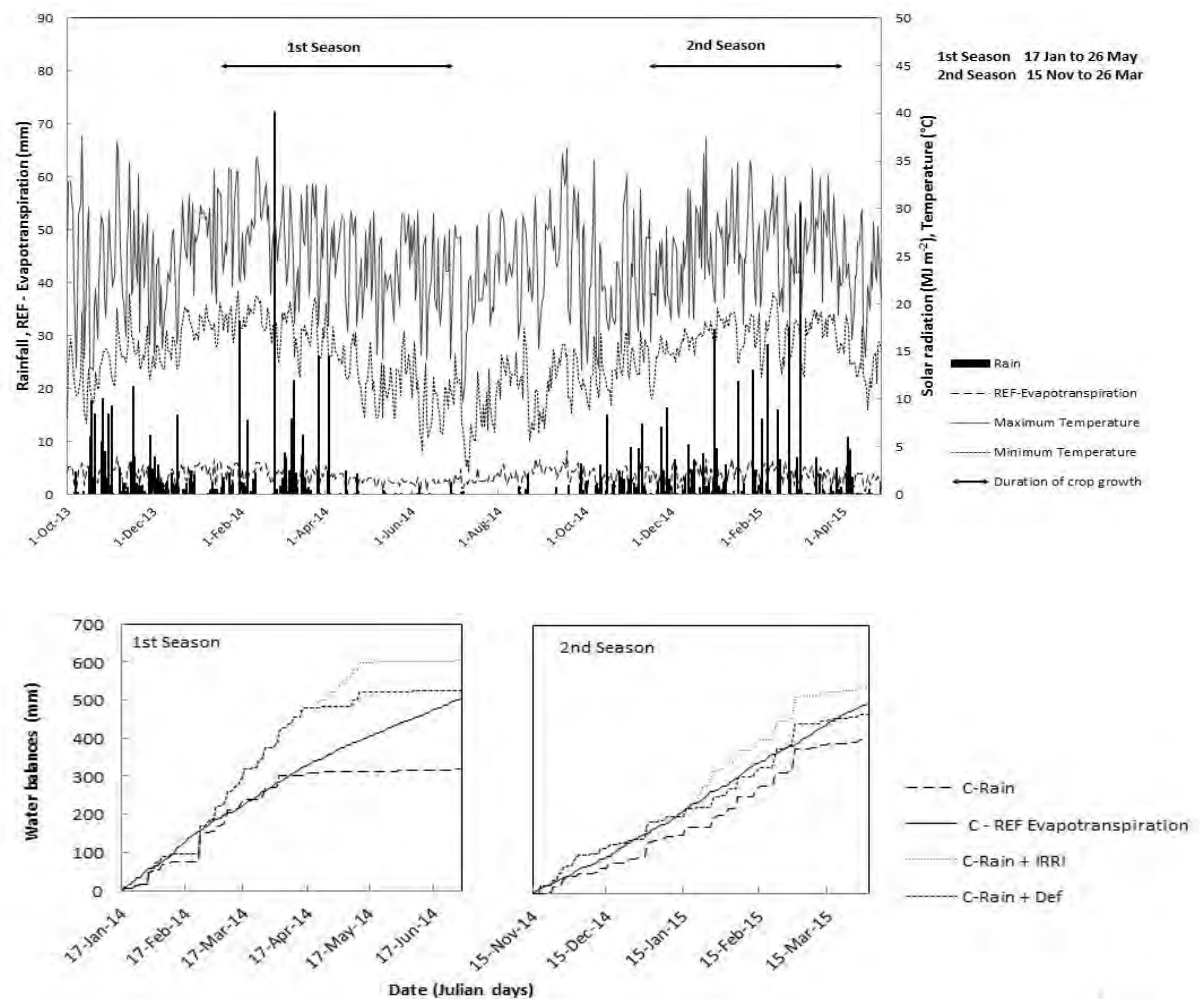
Figure 1: Daily temperature (maximum and minimum) and reference evapotranspiration (REF –Evapotranspiration), and a comparison between cumulative rainfall, REF - evapotranspiration for Ukulinga, KwaZulu–Natal South Africa.

Soil water content

Soil water content was different across seasons, soil layers, water regimes and intercropping treatments (Fig 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 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). 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 range 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) (Figure 2).

Crop physiology

Interaction of water regime and cropping system significantly (P<0.05) influenced sorghum CCI in each growing seasons (Fig 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. 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 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 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 3). During 2014/15, the trend for sorghum RWC was FI (82.23%) was 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 3). Under FI and RF, leaf RWC of sorghum grown in SB was not significantly different to sorghum grown in SS.
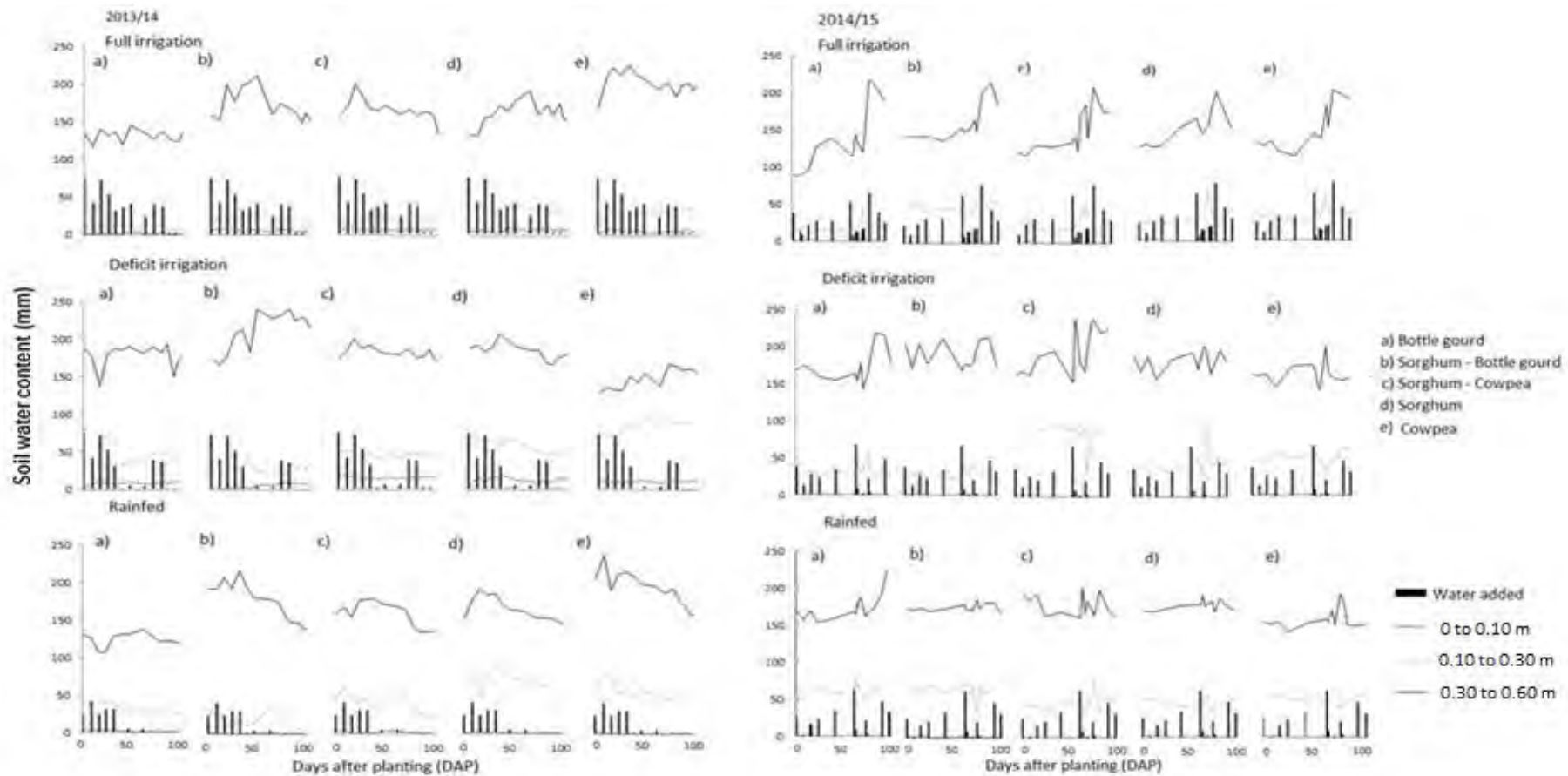
**Figure 2:** Soil water content (mm) at depths 0 – 0.10 m, 0.10 – 0.30 m and 0.30 – 0.60 m for the different cropping systems (sole sorghum (S), sole cowpea (C), sole bottle gourd (B), sorghum – cowpea (SC) and sorghum - bottle gourd (SB) grown under different water management regimes (full irrigation (FI) deficit irrigation (DI) rainfed conditions (RF)) for 2013/14 and 2014/15 planting season.

Significant variations ($P < 0.05$) were observed for g_s of sorghum in response to the interaction of water regime and cropping system (Fig 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}) and (Fig 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 stomatal conductance over time across water regime were in response to varying weather conditions (relative humidity and air temperature) and differences in available SWC caused by rainfall and irrigation events prior to sampling.

Water regime also significantly ($P < 0.05$) affected stomatal conductance for both cowpea [FI (345.76) < DI (376.64) < RF (389.67 mmol m-2 s-1)] and bottle [FI (376.98) < DI (386.64) < RF (456.75 mmol m^{-2} s^{-1})] .Canopy characteristics

Significant differences ($P < 0.05$) in sorghum crop growth were observed in response to season, intercropping and water regime, as well as interactions of water regime and cropping system (Fig. 4). During the 2013/14 growing season, interaction of water regime and cropping system resulted in significant ($P < 0.05$) differences in sorghum plant height and leaf number. Across water regimes, the observed trend was FI > DI > RF for plant height (65.76, 58.81, 56.54 cm, respectively) and leaf number (6.17, 5.97 and 5.90, respectively) (Fig. 4). Under DI and RF conditions, sorghum intercropped with cowpea was significantly taller (7.89%) relative to sorghum grown in SS while the reverse was observed under SB (-8.14%). Results showed that leaf number for sorghum intercropped with either cowpea or bottled responded differently under different water regimes and across the seasons. In 2013/14 intercropping sorghum with cowpea or bottle gourd significantly improved leaf number by an average of 2.3% under FI. In 2014/15, intercropping sorghum with cowpea or bottle gourd significantly reduced leaf number by an average of 6.3% under FI. .
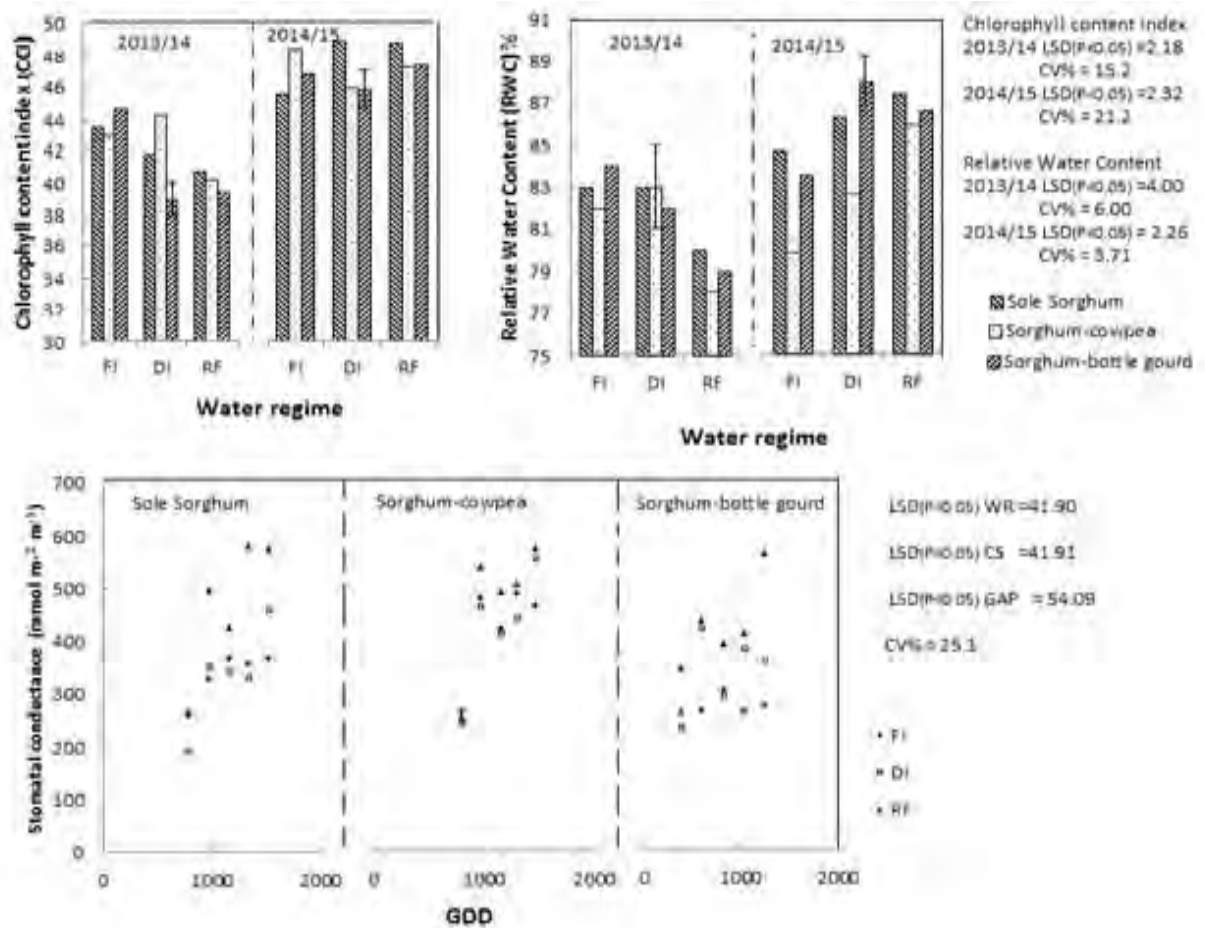
Figure 3: Comparison of sorghum chlorophyll content index (CCI), relative leaf water content (RWC) and stomatal conductance in response to season (2013/14 and 2014/15), cropping system (SS – sole sorghum, SC – sorghum cowpea, SB – sorghum bottle gourd) and water regime (FI – full irrigation, DI – deficit irrigation and RF – rainfed).

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 4). The trend for sorghum plant height was RF > DI > FI (69.33, 67.34 and 66.34 cm, respectively) (Fig 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 (10.00%) 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. 4). Significant differences (P < 0.05) were observed for tillering in response to water regime during 2013/14. Although nominal, tillering was higher under FI (0.2 tillers) followed by DI (0.1 tillers) while no tillers were observed under RF conditions (Fig 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 was 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 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 4). This was more evident during 2014/15 compared with 2013/14 season. During 2013/14 growing season, although differences were nominal 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.

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 4). Conversely, in 2014/15, overall LAI calculated from measurements of total LA of both the sorghum and the intercrop (either cowpea or bottle gourd) was substantially (P < 0.05) improved (86.96% and 115.13%) when intercropped with cowpea (SC) and bottle gourd (SB), respectively. Based of 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).
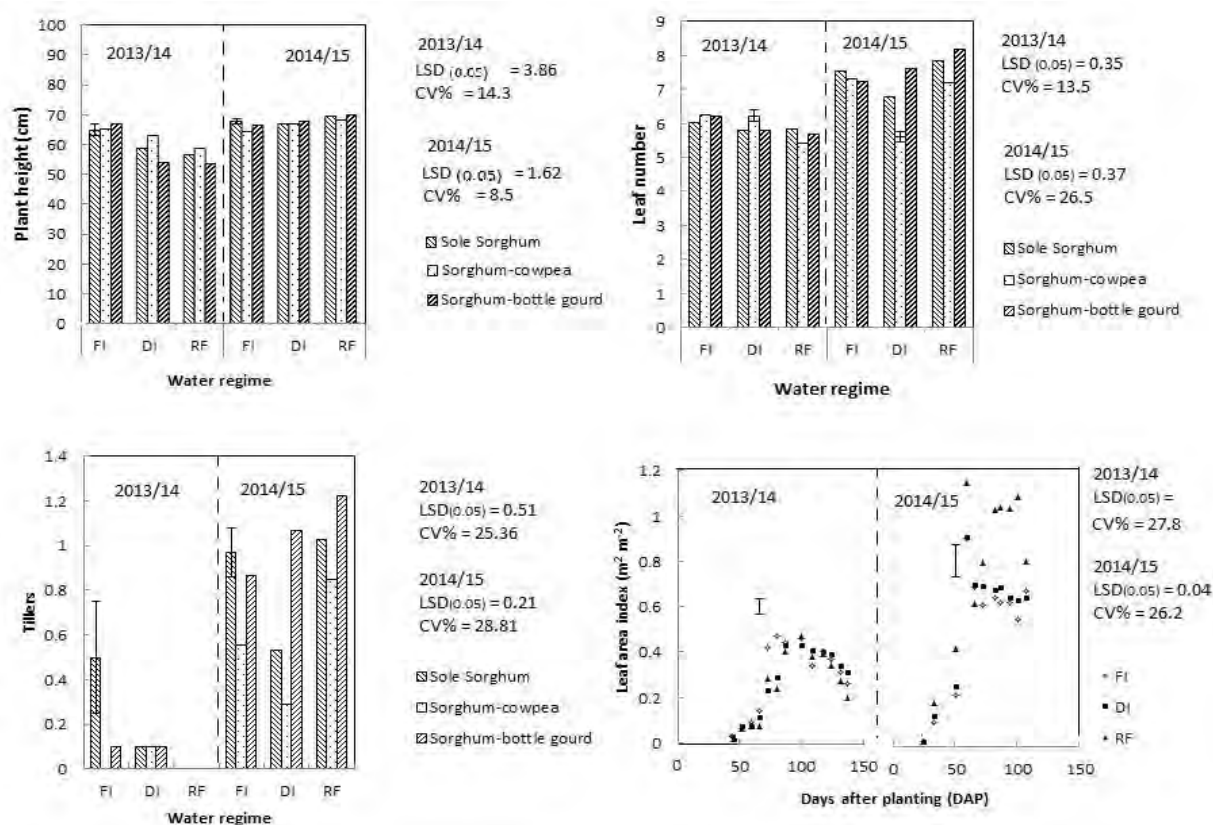
Figure 4: Comparison of sorghum growth parameters and chlorophyll content index measurements in response to intercropping and different water regimes.

Crop phenology

Intercropping and water regime did not have a significant effect on sorghum 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 2014/15 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.

Yield and yield components

Final biomass yield for sorghum was significantly ($P < 0.05$) influenced by the interaction of season and water regime (Table 3). 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 3). 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 3). Final biomass for sorghum grown under DI did not vary significantly across the two growing seasonsYield 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 3).

Final biomass of cowpea was significantly ($P < 0.05$) affected by the interaction of season and cropping system (Table 3). Final biomass was 500% higher during 2014/15 in contrast to 2013/14. This was attributed to increased growth, and increased canopy size experienced during 2014/15. No yield was recorded for cowpea during 2014/15 but during the 2013/14 season yield under FI and DI 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 (Appendix 1).

Final biomass for bottle gourd was significantly ($P < 0.05$) affected by season and cropping system interaction and ($P < 0.05$) affected water regime. Bottle gourd biomass was 9.16% higher during 2014/15 relative to 2013/14 (Table 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 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.

Table 2 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 B[4]	Y[5]	HI[6]	Cowpea B	Y	HI	Bottle gourd 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) 2. Means followed by the same letter indicate that they were not significantly different (p < 0.05) from each other;3 *, ** and *** significant difference at P < 0.001 P < 0.01 and P < 0.05 4 Final biomass; 5 Yield6 Harvest index

Land equivalent ratio

The productivity of the intercrop systems was evaluated using land equivalent ratio (LER) (Fig 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. 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 complimentary responses observed between sorghum and cowpea. Across water regimes, the trend in LER was such that RF (1.61) > FI (1.51) > DI (1.28) (Fig. 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 increased water availability in 2014/15. In 2013/14, intercropping sorghum with cowpea under FI and RF was more productive (10.757%) than intercropping it with bottle gourd.
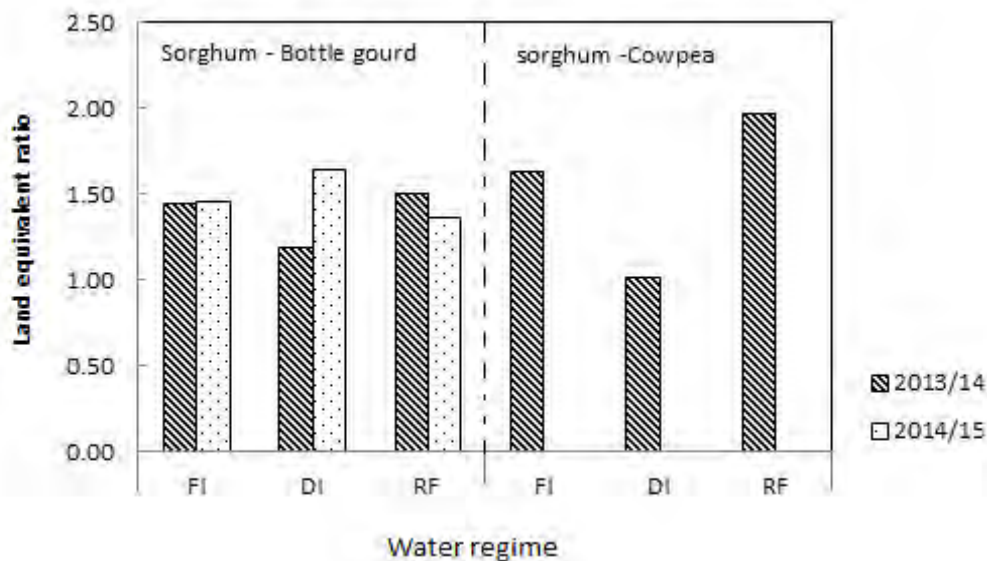
Figure 5: Comparison of land equivalent ratio of different of the different intercrop system in response to the different water regimes.

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 4). This was consistent with water added under each water regime (FI > DI > RF) and larger canopy size of all cropping systems during the 2014/15 growing season (Fig 4 and Table 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) increased WU (11.45 and 4.42%, respectively) relative to sole sorghum (SS) (Table 4). Under FI and DI, intercropping sorghum with cowpea increased 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 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). On average, intercropping resulted in a marginal improvement (2.13%) in WU relative to sole sorghum (SS). Under FI and DI, SB increased 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 4).

Although not statistically significant, WUE calculated on the basis of 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 4). Increasing the WU (the denominator) with a fixed biomass (the numerator) reduced WUE$_b$.

Overall, intercropping (with cowpea and bottle gourd) increased 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. 4) and similarities in WU (Table 4) of the systems relative to SS. Highest (105.56%) ΔWUE$_b$ was observed under DI conditions relative to RI and FI (Table 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 on the basis of 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 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 4). This was attributed to improved productivity of intercrop systems relative to SS (Fig. 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 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 4). This was associated with higher biomass production and yield.

Table 3: 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.

Water regime	Cropping system	2013/14				2014/15			
		Water use (mm)	WU[3] improvements (%)	WUEb[4] kg ha-1 mm-1	WUEg[5] kg ha-1 mm-1	Water use (mm)	WU improvements (%)	WUEb kg ha-1 mm-1	WUEg 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

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 water table relative to soil surface was closer under FI. Water table of a soil is defined as the boundary layer between unsaturated and saturated soil zone caused by ground water within a soil profile. 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 table is 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 were able to minimize unproductive losses of water (primarily soil evaporation) and improve its soil water availability. Cowpea and bottle gourd may have modified the micro–climate within the canopy such that air movement was minimized 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 gs) 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 CO2 absorption. Under limited water conditions, the observed physiological response (CCI and gs) of sorghum intercropped with cowpea highlights one of the benefits of

cereal-legume intercrop systems. Leguminous crop species fix atmospheric nitrogen in to 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, gs 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 which acted as mulch, reducing soil evaporation. 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 RWC for intercropped sorghum observed in the current study fits within this range. In addition, observed RWC was this is in line with observed SWC would also suggest that sorghum was not severely stressed. Nevertheless, to minimize the competitive interaction between sorghum and cowpea, the plant population of cowpea can be reduced so as 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 due to a reduction in canopy size. Photosynthesis becomes substrate limited resulting in less C fixed 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 increasein 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 also 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.

Water use efficiency is an important yield determinant under water stress (Molden et al., 2010). Water use efficiency can be increased either by increasing output with a fixed water input or reducing water input with a fixed output. Observed results of increase in WUE for sorghum biomass (WUEb) and yield (WUEg) 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. 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). The association of HI, WUEg and WUEb was described by Pereira (1996) who stated that WUEg was the product of HI and WUEb. 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 so as to improve soil water availability during the subsequent growing season.

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 perspective. Cowpea and bottle gourd were able to improve soil water availability by minimizing soil evaporation. In addition, cowpea could have been able to improve nutrient availability for sorghum and hence improving 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 need for future research on the root-shoot responses of intercropped sorghum to varying levels of water availability, focusing more on root interactions. Then again, results are largely inconclusive due to poor experimental control over unexpected hazards.

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CHAPTER 5

SORGHUM RADIATION USE EFFICIENCY AND BIOMASS PARTITIONING IN A SORGHUM-COWPEA-BOTTLE GOURD INTERCROP SYSTEM

Running title: Radiation use efficiency of sorghum intercrop systems

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Abstract

Water stress affects radiation use efficiency (RUE) of cropping systems. It was hypothesized that intercropping sorghum (S) with either cowpea (C) or bottle gourd (B) would improve productivity and RUE. This was assessed using a split–plot arrangement with sub–plots [intercrop combinations: SS (sole), C (sole), B (sole), SC (intercrop) and SB (intercrop)] nested in a randomised complete block arrangement within main plots [water regimes: full irrigation (FI), deficit irrigation (DI) and rainfed (RF)]. Data collected included specific leaf area (SLA), leaf area index (LAI) as well as biomass accumulation and partitioning. Extinction coefficient (K), intercepted photosynthetic active radiation (IPAR) and RUE for biomass and grain were also determined. Across water regimes, mean SLA was FI (145) > DI (143) > RF (142 m^2 g^{-1}). A significant (P < 0.05) reduction in SLA was observed when sorghum was intercropped with either C (-19.68%) and SB (18.56%) relative to sole sorghum (SS). Under RF conditions, intercropping S with either C (25.92%) or B (62.36%) significantly (P < 0.05) increased LAI relative to sole sorghum (SS). Under FI, sorghum stems constituted a larger proportion (62%) of final biomass in comparison to DI (52%) and RF (50%). At sorghum flowering, the K value for S (0.59), C (0.61) and B (0.59) were similar. Overall, intercropping S with either C or B improved IPAR (38.26%) and RUE (8.96%) under RF conditions. From a cropping systems point of view intercropping should be recommended for semi – and arid environments since it improves RUE.

Introduction

Within semi-arid and arid regions of sub-Saharan Africa (SSA) rainfed agricultural systems are affected by numerous constraints and chief among them is water scarcity (Rockström et al., 2003). It is also in these regions where population growth rates and food insecurity remains significantly high (Hanjra & Qureshi, 2010). Conversely, infrastructural and financial resources remain inadequate to invest in irrigation technologies to supplement rainfed systems (Drechsel & Dongus, 2010). To increase food production, crops adapted to low water availability, such as, sorghum should be promoted. Due to traits such as deep prolific root systems, stay green characteristics, leaf rolling and osmotic adjustment, sorghum is able to efficiently use available water, and thus confer high tolerance to water stress. Although sorghum is ideal for low rainfall areas, field experiments have observed that yield and biomass production is still compromised by water stress. It could be that, under water stress, sorghum traits that confer its drought tolerance could inadvertently reduce amount of radiation intercepted – an essential resource for biomass and yield production.

Under optimum water and nutrient conditions crop biomass accumulation is primarily influenced by the amount of intercepted photosynthetically active radiation (IPAR) (wavelength in the range of 0.4 – 0.9 um) by the green leaf canopy and the photosynthetic efficiency of its conversion (Curt et al., 1998). Under water–limited conditions, plants reduce canopy size so as to minimise transpirational water loss, resulting in a reduction in total IPAR (Collino et al., 2001). In addition, stomatal conductance is lowered in response to decreasing plant water potential resulting in a reduction in net assimilation rate of carbon for biomass production (Reddy et al., 2014). Therefore, RUE will vary considerably with water availability (Collino et al., 2001; Sekhon et al., 2010; and Bat-Oyun et al., 2012). This has been attributed more to its effect on the use of assimilates for biomass production than canopy size. As a way of improving productivity in rainfed cropping systems, there is need to introduce strategies that improve resilience to water stress while at the same time not compromising the efficient use of readily available resources such as solar radiation.

To increase the efficient use of plant resources, intercropping is fast becoming an approach of choice across diverse agro–ecologies (Keating and Carberry, 1993; Tsubo et al., 2003; Gao et al., 2010; Yang et al., 2011). By definition, intercropping is the practice of growing more than one crop on the same piece of land at the same time. When complementarity of crop species is realized, intercropping has been observed to improve

productivity through spatial and temporal use of resources relative to sole cropping. This is achieved through crop morpho– and eco–physiological modifications (Mabhaudhi and Modi, 2014; Chimonyo et al., 2015). The additional crop introduced into the main crop hastens time to full canopy cover thus reducing amount of water lost through soil evaporation. Increased root density increases access to water that would have also been lost through drainage. The hastened time to full canopy cover would suggest that IPAR is also increased. Conversely, improved water availability and its access implies that stomatal conductivity is maintained resulting in high net assimilation rates and biomass production. This would insinuate that, under water–limited conditions, intercropping could stabilise the derivatives of RUE therefore improving biomass production and yield.

The association between water, radiation interception and plant growth rate has been studied thoroughly in monocropping systems. Information on the improved water and radiation use by intercrop systems is widely available; however these aspects are often investigated separately. Assessing the relationship between water availability and RUE creates an opportunity to improve productivity of intercrop systems. Furthermore, it increases our understanding of symbiotic resource use within the intercrop system. The aim of the study was to determine RUE for sorghum intercropped with either cowpea (*Vigna unguiculata L.* Walp) or bottle gourd (*Lagenaria siceraria*) under varying water regimes. Therefore we investigated effects of intercropping and varying water regimes on the eco-physiological responses of sorghum and its subsequent effect on RUE

Materials and methods

Data collection

Experiment overview

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 (2012/13 and 2013/14). For full description of experimental site refer to Chimonyo et al. (under review).

The field experiment was set up as a split–plot arrangement with sub–plots nested in a randomised complete block design within the main plot, and replicated three times. The main plot was water regime with three levels (full irrigation, deficit irrigation and rainfed). Sub–plots comprised intercrop combinations, sole sorghum (SS), sole cowpea (C), sole bottle

gourd (B), sorghum – cowpea (SC) and sorghum – bottle gourd (SB). For full detail on treatments and plot layout, refer to Chimonyo et al (under review). All cultural practices such as weeding, fertilizer application rates and pest management were done according to best management practices for the site.

Overall, more rainfall (26.31%) was received in 2014/15 than in 2013/14 (Table 1). Cumulative reference evapotranspiration was marginally higher (2.93%) in 2013/14 (502.61mm) than in 2014/15. A deficit of 184.14 and 91.49 mm for 2013/14 and 2014/15, respectively was, therefore, recorded (Table 1). During 2013/14 irrigation applied in the FI and DI treatment was 286.50 and 208.0 5mm, respectively. During 2014/15 irrigation applied in the FI treatment was 208.05 and 136.00 mm, respectively. 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).

Table 1: A comparison of water applied across the water regimes (Full irrigation, deficit irrigation and rainfed conditions) and observed Reference evapotranspiration (ET$_O$). Values in bold represent total water added (irrigation and rainfall) into the system.

	Full irrigation		Deficit irrigation		Rainfed conditions	Reference evapotranspiration
2013/14	286.50	**608.97**	208.05	**530.52**	322.47	502.61
2014/15	208.05	**610.31**	136.00	**538.26**	402.26	493.75

Crop growth parameters

Specific leaf area (SLA) (cm^2 g^{-1}) was defined as the one-sided area of a fresh leaf divided by its oven dried mass. Specific leaf area was determined from plant samples that were destructively taken on a weekly basis. Immediately after sampling, leaf area was measured using an LI-3100C leaf area meter (LI-COR, USA). Thereafter, leaves were oven dried at a constant temperature of 85°C until a constant mass was attained. Specific leaf area was calculated as:

$$SLA = \frac{LA}{LM} \, (m^2 g^{-1})$$
<div align="right">Equation 2</div>

where SLA = specific leaf area (m^2 g^{-1}), LA (m^2) is the one-sided area of a fresh leaf, and LM is the oven dried mass of leaves.

The remaining plant parts were separated into stalk/stems and reproductive organs and were also dried. Mass of leaves, stems and reproductive organ was used to determine biomass accumulation (total mass) and partitioning.

Leaf area index (LAI) measurements were taken during midday (1200–1400 hrs.) on days with clear skies using the AccuPAR-LP80 ceptometer (Decagon Devices, USA). In addition, LAI was also determined from measurements of leaf area as described in chapter 4.The AccuPAR–LP80 also provided measurements of incident photosynthetic active radiation (I$_i$) and below canopy measurements of PAR (I$_o$). Due to unavailability of equipment in the beginning of the 2013/14 season, results for I$_i$, I$_o$ and LAI from flowering of sorghum to its soft dough stage were presented. On the other hand, data on I$_i$, I$_o$ and LAI from end of juvenile stage upto soft dough stage of sorghum for 2014/15 growing season were available. However, for the sake of comparison, data at flowering of sorghum to its soft dough stage for 2014/15 growing season were presented.

Radiation interception and RUE:

Radiation interception by a multiple layer canopy such as those of intercrop systems has been outlined by Tsubo et al. (2005). The transmission of radiation through the canopy and canopy layers is determined by the extinction coefficient (*K*). Although *K* value for any given crop is often assumed to be constant across different ecosystems, under limited water availability it can change due to changes in leaf orientation. Using *K* values of sorghum, cowpea and bottle gourd were estimated from sole stands for the three water regimes using the Beer–Lambert law:

$$K = (-In \frac{I_i}{I_o})/LAI \qquad \qquad \text{Equation 3}$$

where *K* is the extinction coefficient, I$_i$ is radiation under the canopy, I$_o$ is radiation above the canopy and LAI is the leaf area index (m^{2}m^{-2}) *In* is natural log. Please note LAI was determined from measurements of leaf area as described in chapter 4.

Depending on the number of component crops, radiation will travel down different layers of an intercrop canopy. Each layer is determined as the canopy height of component crop and

it is assumed that the each layer is horizontally homogeneous. In this study, the first layer was represented by the sorghum canopy less the height for either cowpea or bottle gourd canopy (Equation 3). The second layer was represented by cowpea or bottle gourd in interaction with sorghum (Equation 4) at the same corresponding heights. The two layers for sorghum represented by the following equations:

$$LAI_{C1} = (1 - n)LAI_C \qquad \text{Equation 4}$$

$$LAI_{C2} = nLAI_C \qquad \text{Equation 5}$$

where LAI_{C1} is sorghum LAI in the over storey, LAI_{C2} is sorghum LAI in the understory, LAI_C is sorghum LAI in the sole crop and n is the ratio of plant/canopy heights of sorghum and cowpea or bottle gourd,. Equation 1 and 2 assume that the distribution of leaves in canopies LAI_{C1} and LAI_{C2} is random.

The amount or fraction of radiation intercepted by sorghum in the first layer (over storey) was given as

$$F_{C1} = 1 - \exp(-K_C \times LAI_{C1}) \qquad \text{Equation 6}$$

where F_{C1} is the fraction of radiation intercepted by sorghum in the first layer, LAI_{C1} is LAI for sorghum less the height of cowpea or bottle gourd and K_C is sorghum canopy extinction coefficient. To determine the fraction of radiation intercepted by the sorghum and cowpea or bottle gourd understory, the equation described by Keating and Carberry (1993) was used:

$$F_{C2} = \frac{K_C \times LAI_{C2}}{K_C \times LAI_{C2} + K_{L/B} \times LAI_{L/B}} \times \left[1 - \exp\left(-K_C \times LAI_{C2} - K_{\frac{L}{B}} \times LAI_{\frac{L}{B}}\right)\right] \qquad \text{Equation 7}$$

$$F_{L/B} = \frac{K_{L/B} \times LAI_{L/B}}{K_C \times LAI_{C2} + K_{L/B} \times LAI_{L/B}} \times [1 - \exp(-K_C \times LAI_{C2} - K_{L/B} \times LAI_{L/B})] \qquad \text{Equation 8}$$

where F_{C2} is the fraction of radiation intercepted in the second layer, $F_{L/B}$ is the fraction of radiation intercepted by either cowpea (L) or bottle gourd (B). LAI_{C2} is LAI for sorghum at the same height as cowpea or bottle gourd, $LAI_{L/B}$ is LAI for either cowpea (L) or bottle gourd (B). $K_{L/B}$ is crop canopy extinction coefficient for cowpea or bottle gourd.

Thereafter, radiation use efficiency for the sole (Equation 8) and intercrop (Equation 9 and 10) systems was calculated as follows:

$$RUE = \frac{Y/BM}{IPAR}(MJ\ PAR)$$ Equation 9

$$RUE_{SC} = \frac{Y/BM_S}{IPAR_S} + \frac{Y/BM_C}{IPAR_C}(MJ\ PAR)$$ Equation 10

$$RUE_{SB} = \frac{Y/BM_S}{IPAR_S} + \frac{Y/BM_B}{IPAR_B}(MJ\ PAR)$$ Equation 11

where RUE = Radiation use efficiency (MJ PAR^{-1}), biomass (BM) yield (kg ha^{-1}), Y/BM$_{S/C/B}$ is the economic (Y) (kg ha^{-1}) or final biomass (BM) yield (kg ha^{-1}) for sorghum, cowpea or bottle gourd in the intercrop system, IPAR is Intercepted PAR, and IPAR$_{S/C/B}$ is PAR intercepted by sorghum, cowpea or bottle gourd in the intercrop system.

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 the data collected therefore data were analysed separately. 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) least significant differences (LSDs) in GenStat® at the 5% level of significance. Standard errors of means (SEs), and corresponding degrees of freedom (d.f.) were presented in tables and figures.

Results

Leaf area index

Although seasonal effects on LAI for the cropping systems were not statistically analysed, results showed that it was higher (99.35%) during the 2014/15 growing season in comparison to 2013/14 at sorghum flowering to its soft dough stage. Interaction of water regime and cropping system significantly ($P < 0.05$) influenced sorghum LAI for each growing season (Fig 1). During the 2013/14 growing season, intercropping sorghum with either cowpea or bottle gourd improved cropping systems' LAI by 26.35% and 29.52 %, respectively, relative to sole sorghum. Overall, water regime had no significant effect on sorghum LAI. Under FI, intercropping sorghum with bottle gourd resulted in an increase (47.85%) in the systems' LAI

relative to sorghum – bottle gourd grown under DI (28.36%) and RF (15.26%) (Fig 1). During the 2014/15 growing season, similar to the observed trend during the 2013/14 season growing season, water regime did not have a significant effect on sorghum LAI. However, intercropping sorghum with either cowpea or bottle gourd improved the systems' LAI by 112.24 and 65.26%, respectively. Under RF conditions, intercropping sorghum with either cowpea or bottle gourd resulted in a high (3.35 and 3.21 m^2m^{-2}) LAI relative to when the same cropping systems were grown under DI (2.89 and 2.25 m^2m^{-2}) and FI (2.51 and 1.35 m^2m^{-2}) conditions. This was consistent with observed results of biomass production and accumulation (Fig 1).

Fig 1: Comparison of sorghum leaf area 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). Error bars represent mean ± SE (n = 13). SEs for 2013/14 LAI = 0.14; d.f. = 118; P < 0.05. SEs for 2014/15 LAI = 0.18; d.f. = 178; P < 0.05.

Specific leaf area

Significant (P < 0.05) interactions between water regime and cropping system were observed for sorghum SLA during each growing season (Fig 2). The overall trend for sorghum SLA across water regimes and cropping systems was closely associated with phenological development. There was a sharp increase in SLA from end of juvenile stage (495 and 213 GDD for 2013/14 and 2014/15, respectively) up to the point of floral initiation (987 and 639

GDD) (slope = 0.54 and 2.13 and r^2 = 0.72 and 1.00 for 2013/14 and 2014/15, respectively). These results are consistent with low leaf dry mass relative to leaf area observed during this time period and low stomatal (Chimonyo et al., under review). From floral initiation to boot stage (1235 and 789 GDD for 2013/14 and 2014/15, respectively) there was an observed sharp decreased of SLA (slope = -0.53 and -0.82 and r^2 = -0.76 and 0.82 for 2013/14 and 2014/15, respectively) (Fig 2). The sharp decrease could be associated with increase in leaf dry mass relative to leaf expansion. Thereafter, SLA gradually declined (slope = -0.11 and -0.09 and r^2 = 0.89 and 0.85 for 2013/14 and 2014/15, respectively) until soft dough stage. During 2013/14, the observed trend across water regimes, was FI (139.34 m^2 g^{-1}) < DI (148.72 m^2 g^{-1}) < RF (160.31 m^2 g^{-1}). The opposite was true during 2014/15 such that FI (145.34 m^2 g^{-1}) > DI (138.72 m^2 g^{-1}) > RF (130.31 m^2 g^{-1}). For both seasons and across water regimes, SLA was negatively associated with chlorophyll content index (CCI). However these results were inconsistent to observed results of SWC for the water regimes (Chimonyo et al., under review). While the trend observed during 2014/15 was consistent with results of stomatal conductance (g_s) (Chimonyo et al., under review). Under RF conditions, intercropping resulted in sorghum with low SLA [SC (-16.98 and -22.56%) and SB (-20.79 and -16.47%) for 2013/14/ and 2014/15, respectively] relative to sole sorghum (SS). This was consistent with increased CCI and g_s for the intercropped sorghum also relative to SS (Chimonyo et al., under review). The reduced SLA could also be associated with overall improvements in (Chimonyo et al., under review). Under FI, intercropping sorghum with cowpea increased SLA of sorghum relative to SS by 17.81 and 2.46% during 2013/14 and 2014/15, respectively (Fig 2).
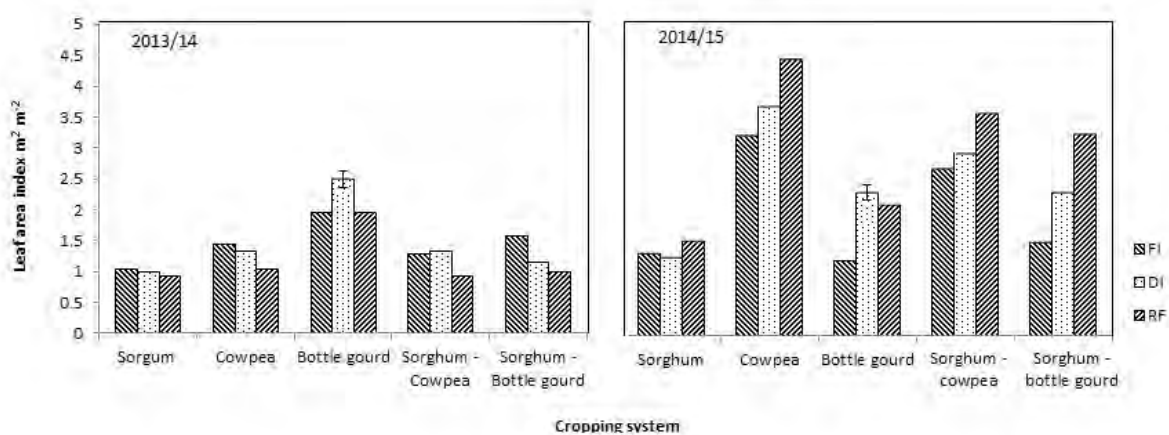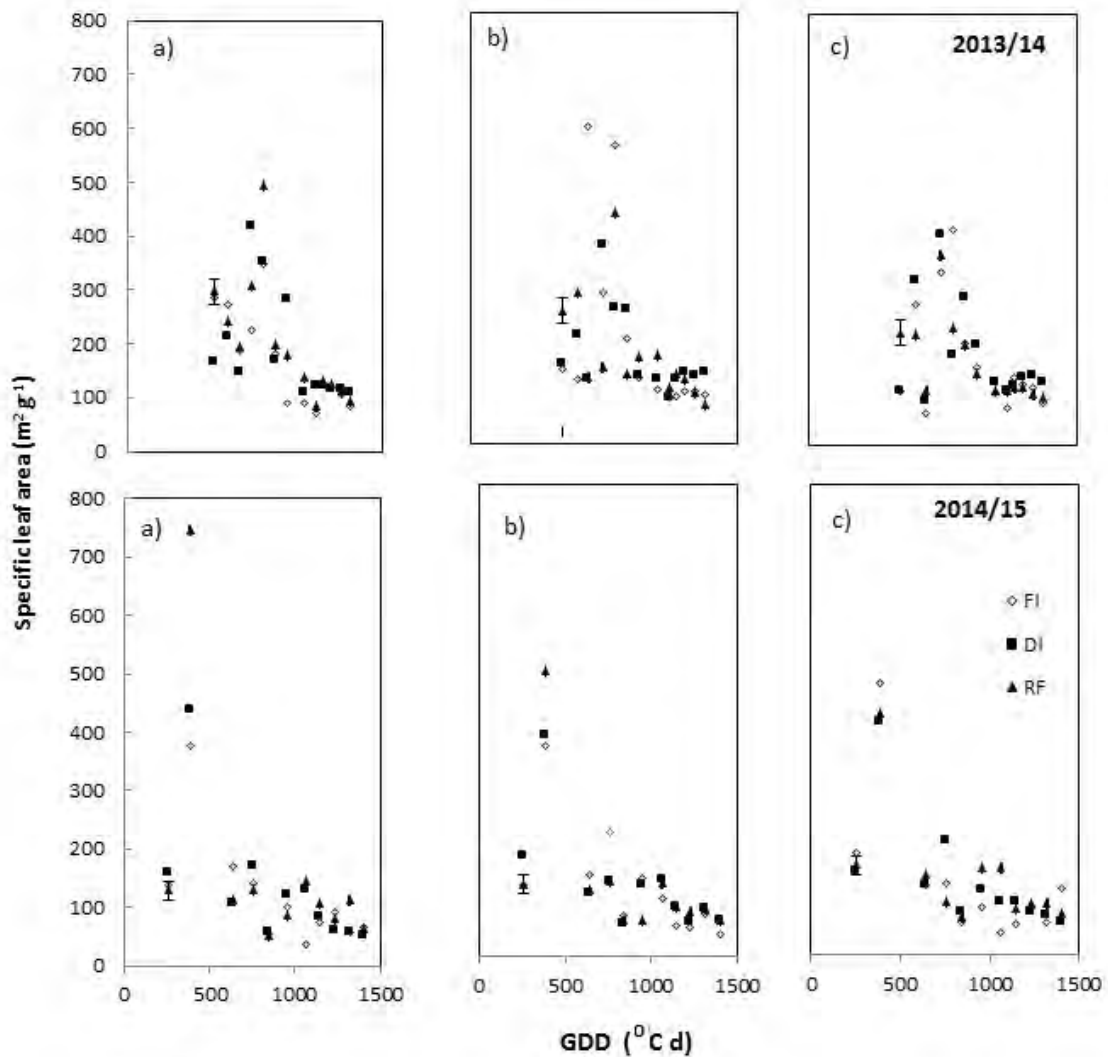
Fig 2: Comparison of sorghum specific leaf area in response to season (2013/14 and 2014/15), cropping system [(a) – sole sorghum, (b) – sorghum cowpea, (c) – sorghum bottle gourd] and water regime (FI – full irrigation, DI – deficit irrigation and RF – rainfed). The error bar represents mean ± SE (n = 13). SEs for 2013/14 SLA = 48.61; d.f. = 232; P < 0.05. SEs for 2014/15 SLA = 32.12; d.f. = 196; P < 0.05

Extinction coefficient

For both seasons, water regime did not have a significant effect on *K* values for sorghum, cowpea and bottle gourd. It was observed that *K* values for the crop species were significantly (P < 0.05) different across the different developmental stages of sorghum (Table 2). For sorghum, the trend was such that there was a 31% increase in the *K* value between end of juvenile and floral initiation stage. Thereafter, there was a gradual increase of 11% between floral initiation and the appearance of the flag leaf stage. Similar to sorghum, the trend for *K*

value for cowpea and bottle gourd was such that there was a sharp increase in the K value (19.23 and 47.9%, respectively) between end of juvenile and floral initiation. Thereafter, there was a gradual increase (16.13 and 28.81%, respectively) in the K value between floral initiation and flowering (Table 2). The increase in K value could be attributed to an increase in LAI brought about by increase in leaf number, tillering of sorghum and branching of cowpea and bottle gourd (Chimonyo et al., under review).

Table 2: A comparison of extinction coefficient for sorghum, cowpea and bottle gourd calculated at different sorghum phenological stages.

Developmental stage of sorghum	Sorghum	Cowpea	Bottle gourd
End of juvenile	0.32a[3]	0.42a	0.22a
Floral initiation	0.52b	0.52b	0.42b
Appearance of flag leaf	0.59c	0.61c	0.58c
Flowering	0.59c	0.62c	0.59c
Grain filling	0.61c	0.62c	0.59c
P$_{(value)}$	0.05	0.05	0.05
SEs[1]	0.02	0.01	0.03
d.f.[2]	4	4	4

[1]SEs Standard error of means between developmental stage for sorghum; [2]d.f. = Degrees of freedom of the error. [3]Numbers followed by a different letter are significantly different at P < 0.05.

Biomass production and partitioning for sorghum

Although seasonal effects on biomass accumulation for sorghum were not statistically analysed, results showed that overall biomass was higher (62.35%) during 2014/15 in comparison to sorghum grown during 2013/14. This was consistent with improved rainfall received during 2014/15 relative to 2013/14 (Table 1). For both seasons, water regime had a significant (P < 0.05) effect on total biomass and biomass partitioning of sorghum (Fig 3) while no differences were observed due to cropping system. During 2013/14 the trend was such that, before floral initiation, biomass partitioned to leaves relative to stem was high (61%- leaves / 39 %- stems). It was observed that the ratio was higher under FI (67% / 33%) compared to DI and RF (57% / 43% and 58 / 42%, respectively) (Fig 3). At boot stage, biomass partitioned to leaves relative to stems reduced and this reduction was more pronounced when sorghum was grown under FI (31% - leaves / 69% - stems) vs DI and RF (38% / 62% and 36% / 64%, respectively). At harvest, the trend for grand mean for biomass

partitioning was stem (50%) > leaves (30%) > panicle (20%). Panicle mass did not vary significantly across the water regimes [FI (20), DI (20) and RF (25%) of final mass]. Under FI, stems constituted a larger proportion (62%) of final biomass in comparison to stem biomass of sorghum grown under DI and RF (52 and 50%). On the other hand, leaves produced under FI had the least contribution (18%) to final total biomass while under DI and RF they contributed consubstantially (28 and 25%, respectively) (Fig 3).

During 2014/15, it was observed that the trend for leaf and stem biomass partitioning was DI (72% / 26%) > RF (68 / 32%) > FI (67 / 33 %). At boot stage, biomass partitioned to leaves relative to stems was low (Fig 3). This reduction was more pronounced when sorghum was grown under RF (31% / 69%) vs DI and FI (37% / 63% and 42% / 58%, respectively). Similarly, at harvest, the trend for biomass partitioning was stem (56%) > leaves (24%) > panicle (20%). Based on mean values of water regimes during 2013/14, sorghum panicle mass was similar [FI (21), DI (20) and RF (19%) of final mass] (Fig 3). It was observed that under RF conditions, stems still constituted a larger proportion (58%) of the final biomass in comparison with stem biomass of sorghum grown under DI and FI (50 and 52 %, respectively). These observations were consistent with the results of SWC which showed high SWC in RF plots relative to FI plots during the 2014/15 growing season (Chimonyo et al., under review). On the other hand, leaves produced under RF had the least contribution (23%) to final total biomass relative to DI and FI (29 and 27%, respectively).
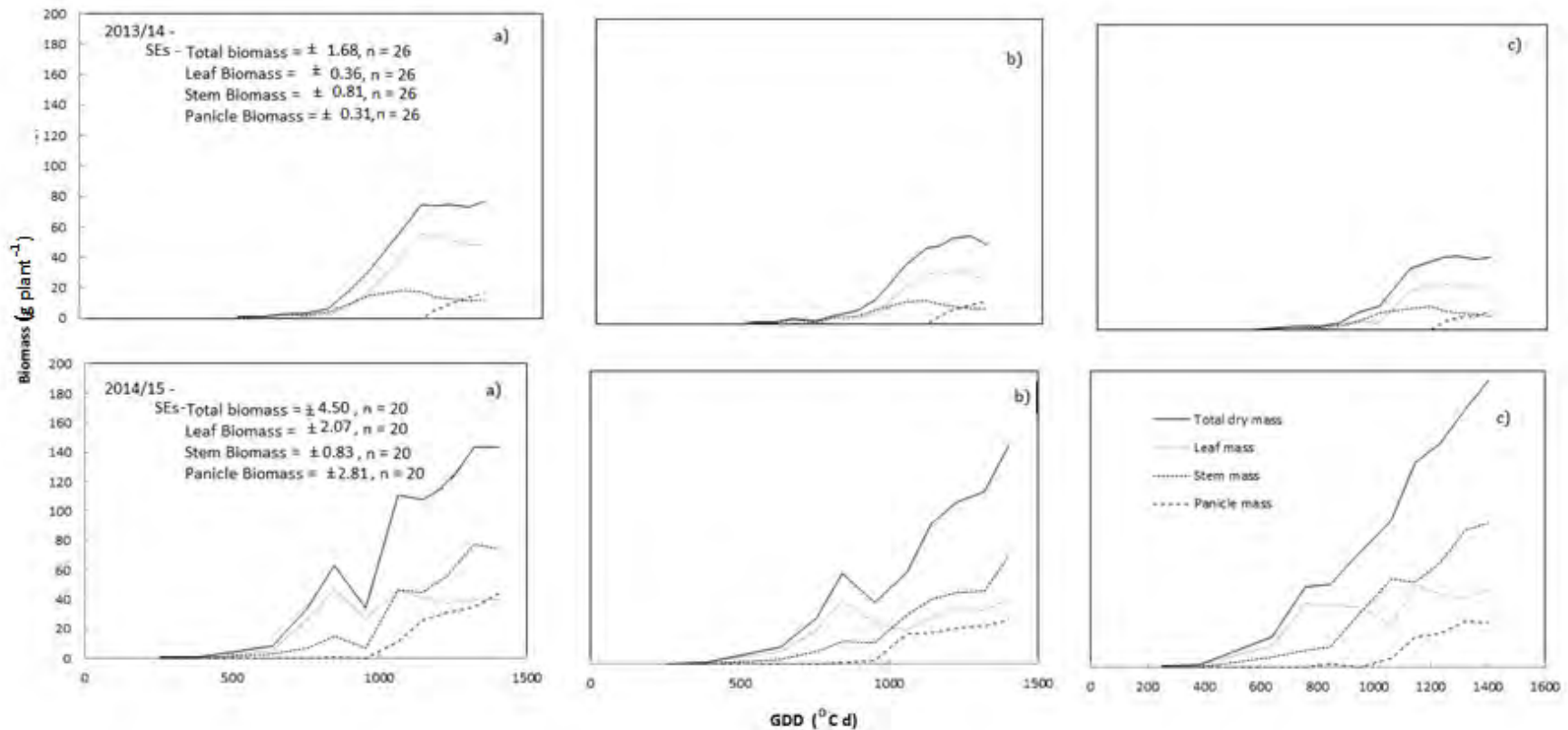
Fig 3: Comparison of sorghum biomass partitioning in to leaf, stem and panicle and biomass, in response to season (2013/14 and 2014/15) and water regime [(a) FI – full irrigation, (b) DI – deficit irrigation and (c) RF – rainfed]. SEs for 2013/14 Total biomass = 3.39; d.f. = 250; P < 0.05. SEs for 2014/15 Total biomass = 9.01; d.f. = 196; P < 0.05. SEs for 2013/14 Leaf biomass = 0.72; d.f. = 250; P < 0.05. SEs for 2014/15 Leaf biomass = 4.15; d.f. = 196; P < 0.05. SEs for 2013/14 Stem biomass= 1.62; d.f. = 250; P < 0.05. SEs for 2014/15 Stem biomass = 1.65; d.f. = 196; P < 0.05. SEs for 2013/14 Panicle biomass = 0.61; d.f. = 250; P < 0.05. SEs for 2014/15 Total biomass = 5.62; d.f. = 196; P < 0.05.

130

Radiation interception and RUE

During the 2014/15 growing season the trend for IPAR for sole sorghum was DI (367 MJ) < FI (384 MJ) < RF (389.00 MJ). This was consistent with LAI observed for each water regime (DI < FI < RF) (Fig 1). Results show that intercropped sorghum had lower (-31%) IPAR relative to SS for all the water regimes (Table 3 and 4). Intercropping sorghum with either cowpea or bottle gourd increased (52.87 and 35.87%, respectively) mean the systems' IPAR relative to SS (Table 3 and 4). When sorghum was intercropped with cowpea, improvements in the systems' IPAR were such that FI (61.25%) > DI (55.26%) > RF (47.56%) relative to SS. When sorghum was intercropped with bottle gourd, improvements in the systems' IPAR were such that FI (17.56%) < DI (44.56%) < RF (45.56%) relative to SS (Table 4).

Although not statistically significant, radiation use efficiency calculated on the basis of biomass (RUE_b) was different across phenological stage, water regime and cropping system. Overall, RUE_b for sorghum increased with each consecutive phenological stage (Table 3 and 4). The trend was such that end of juvenile stage (0.37) < floral initiation (1.58) < appearance of flag leaf (6.20) < flowering (9.42) grain filling (13.70). The observed increase was consistent with observed higher rate of increase in biomass ($r^2 = 0.89$, slope = 0.56) relative to rate of IPAR ($r^2 = 0.62$, slope = 0.25). Intercropping sorghum with either cowpea or bottle gourd improved RUE_b by 88.56% and 95.35%, respectively, relative to SS (Table 3 and 4). This was consistent with increased LAI for SC and SB intercrop systems relative to SS. Intercropping sorghum with either cowpea or bottle gourd resulted in large improvements (136.25%) for RUE_b during early canopy development (end of juvenile stage and floral initiation). For sorghum intercropped with cowpea improvements in RUE_b were RF (142.81%) > FI (88.56%) > DI (36.22%) (Table 3). For sorghum intercropped with bottle gourd improvements in RUE_b were FI (165.94 %) > RF (67.61%) > DI (53.95%) (Table 4).

Table 3: A comparison of intercepted photosynthetic active radiation (IPAR), radiation use efficiency (RUE) and % changes in RUE for sorghum by sorghum – cowpea intercrop system in response to different water regimes (full irrigation, deficit irrigation and rainfed conditions) and sorghum phenological stage (i = End of juvenile, ii = Floral initiation, iii = Appearance of flag leaf, iv = Flowering and v = Grain filling).

Water regime	Phenological stage	PAR[1] (MJ)	IPAR (MJ)			RUE (kg MJ ha^{-1})				Δ RUE (%)
			Sorghum (sole)	Sorghum (F_{C1}[2] + F_{C2}[3])	Cowpea (F_L[4])	Sorghum (sole)	Sorghum (F_{C1} + F_{C2})	Cowpea (F_L)	Total (F_{C1} + F_{C2} + F_L)	
Full irrigation	i	1043.9	56.7	36.1	328.6	0.3	0.5	0.1	0.6	106.67
	ii	1067.2	158.3	96.1	383.4	1.4	1.8	1.7	3.5	152.56
	iii	1058.3	382.8	290.8	543.3	4.8	4.8	1.4	6.6	37.37
	iv	1028.3	402.8	361.1	688.0	5.4	5.8	4.5	10.3	91.64
	v	1063.3	458.3	358.4	680.8	8.1	9.3	3.3	12.5	54.20
Deficit irrigation	i	1022.2	103.3	90.9	260.4	0.3	0.2	0.0	0.2	33.33
	ii	1055.6	315.0	318.3	288.5	0.9	0.8	0.8	1.6	73.08
	iii	1053.9	395.6	375.0	509.9	4.2	4.1	0.8	4.9	16.81
	iv	968.9	471.1	469.3	549.7	5.4	4.4	1.7	6.0	11.30
	v	1063.3	506.7	460.3	568.7	5.8	5.2	3.3	8.5	46.58
Rainfed	i	1062.2	111.7	69.0	270.6	0.2	0.3	0.0	1.1	408.33
	ii	1096.1	292.2	268.1	294.6	1.9	2.0	1.4	3.4	78.10
	iii	1056.1	475.6	327.6	662.6	3.6	3.9	1.4	5.3	47.26
	iv	1050.6	570.0	434.4	664.6	4.6	6.7	2.4	9.1	97.27
	v	1061.7	531.1	436.0	685.8	8.7	11.1	4.9	16.0	83.09

1 Photosynthetic active radiation; 2 Radiation intercepted by sorghum first layer derived from the fraction of radiation intercepted by the first layer; 3 Radiation intercepted by sorghum second layer derived from the fraction of radiation intercepted by the second layer; 4 Radiation intercepted by cowpea

Table 4: A comparison of intercepted photosynthetic active radiation (IPAR), radiation use efficiency (RUE) and % improvements in RUE for sorghum by sorghum – bottle gourd intercrop system in response to different water regimes (Full irrigation, Deficit irrigation and Rainfed conditions) and sorghum phenological stage (i = End of juvenile, ii = Floral initiation, iii = Appearance of flag leaf, iv = Flowering and v = Grain filling).

Water regime	Phenological stage	PAR (MJ)	IPAR (MJ)			RUE (kg MJ ha^{-1})				RUE Improve (%)
			Sorghum (Sole)	Sorghum (F_{C2} + F_{C1})	Bottle gourd (F_L)	Sorghum (Sole)	Sorghum (F_{C2} + F_{C1})	Bottle gourd (F_L)	Total (F_{C1} + F_{C2} + F_L)	
Full irrigation	i	1044.0	56.7	59.6	217.5	0.3	0.3	0.1	1.6	506.67
	ii	1067.2	158.3	96.1	383.4	1.4	3.4	1.2	4.6	228.21
	iii	1058.7	382.8	357.5	598.9	4.8	4.5	1.5	5.9	24.53
	iv	1028.5	402.8	291.7	632.5	5.4	5.4	2.2	7.6	41.13
	v	1063.3	458.3	342.3	705.1	8.1	7.5	3.0	10.5	29.20
Deficit irrigation	i	1022.4	103.3	68.7	269.7	0.3	0.2	0.2	0.4	46.67
	ii	1055.7	315.0	278.8	255.2	0.9	1.2	0.6	1.8	96.15
	iii	1053.9	395.6	355.7	464.5	4.2	4.5	1.0	5.5	32.33
	iv	969.2	471.1	325.8	660.9	5.4	4.6	2.0	6.6	21.92
	v	1063.7	506.7	363.9	558.5	5.8	7.5	2.5	10.0	72.67
Rainfed	i	1062.4	111.7	73.5	176.1	0.2	0.3	0.2	0.4	108.33
	ii	1096.1	292.2	268.1	252.0	1.9	1.4	1.2	2.6	38.10
	iii	1056.5	475.6	327.6	547.6	3.6	4.4	1.7	6.1	67.66
	iv	1050.6	570.0	434.4	658.8	4.6	5.7	2.0	7.6	66.01
	v	1061.9	531.1	436.0	671.8	8.7	9.6	4.2	13.8	57.93

[1] Photosynthetic active radiation; [2] Radiation intercepted by sorghum first layer derived from the fraction of radiation intercepted by the first layer; [3] Radiation intercepted by sorghum second layer derived from the fraction of radiation intercepted by the second layer; [4] Radiation intercepted by cowpea.

Radiation use efficiency calculated on the basis of yield was influenced by growing season, water regime and cropping system. Although not statistically significant, RUE_g for sorghum was high during 2013/14 growing season relative to the 2014/15 season. Overall, intercropping sorghum with bottle gourd resulted in the highest (26.09 %) improvements of RUE_g relative SS and SC (Table 5). During the 2013/14 growing season, the trend for sorghum RUE_g across the water regimes was DI (2.84 kg MJ ha^{-1}) > FI (2.52 kg MJ ha^{-1}) > RF (2.26 kg MJ ha^{-1}). Under DI, intercropping sorghum with cowpea resulted in a reduction (-31.69%) in RUE_g while intercropping with bottle gourd resulted in the highest (39.78%) improvements in RUE_g (Table 5). During the 2014/15 growing season, the trend for sorghum RUE_g across the water regimes was RF (2.01 kg MJ ha^{-1}) > DI (1.95 kg MJ ha^{-1}) > FI (1.99 kg MJ ha^{-1}). Under RF conditions, intercropping sorghum with bottle gourd resulted in highest improvements in RUE_g while the least improvements were observed under F1 (4.10%).

Table 5: Comparison of radiation use efficiency derived from grain yield of sorghum, cowpea and fruit dry mass of bottle gourd for the different cropping systems in response to full irrigation (FI), deficit irrigation (DI) and rainfed (RF) conditions during 2013/14 and 2014/15 growing season.

Growing season	Water regime	Radiation use efficiency (kg MJ ha^{-1})					RUE improvements (%)	
		Sorghum (S)	Cowpea (C)	Bottle gourd (B)	SC	SB	SC	SB
2013/14	FI	2.52	1.88	5.10	2.71	3.20	7.54	26.98
	DI	2.84	0.98	10.27	1.94	3.97	-31.69	39.78
	RF	2.26	1.59	2.76	2.49	2.52	10.1	11.50
Mean		**2.54**	**1.48**	**6.04**	**2.38**	**3.23**	**-4.68**	**26.09**
2014/15	FI	1.95	-	4.53	-	2.03	-	4.10
	DI	1.99	-	3.69	-	2.15	-	8.04
	RF	2.01	-	4.12	-	2.35	-	16.91
Mean		**1.98**	**-**	**4.11**	**-**	**2.17**	**-**	**9.68**

Discussion

The observed response for sorghum LAI would suggest that sorghum canopy development was not sensitive to changes in water availability. Under water stress, plants often respond by reducing canopy size so as to reduce transpiring leaf surface (Razzaghi et al., 2012). This then allows the plant to reduce its demand of water. For crop species like sorghum, water stress triggers morphogenesis so as to adapt. In the event of water stress, sorghum has been observed to increase root sink strength relative to shoot strength so as to increase root volume for efficient water capture. It could be that this drought adaptation strategy allowed for sorghum to maintain its canopy size. On the other hand, intercropping sorghum with either cowpea or bottle gourd increased overall LAI although its sensitivity to water was also increased. One of the advantages of intercropping is that it improves canopy size which allows for use of more resources such as water and radiation (Chimonyo et al., 2015; Tsubo et al., 2003; Keating & Carberry, 1993). Reducing water availability reduced LAI of the intercrop system. This suggests that, even though intercropping increased overall LAI, it could have increased the demand and competition for water, especially under limited availability. Plants therefore responded by reducing canopy size. These results are consistent with Matusso, et al. (2014) and Fan et al. (2013) who also observed a reduction in LAI for intercrop systems in response to reduction in water availability. To reduce the demand and competition for water, relay cropping of cowpea can be done.

The observed changes in SLA over time could be attributed to changes in leaf mass due to changes in source − sink strength in association with leaf expansion rates at different phenological stages. For instance, the low SLA observed during early vegetative development of sorghum could be that the leaves were not actively expanding thus leaf area (LA) was low relative to leaf mass. At this stage source − sink relationship of the young leaves would be at equilibrium since leaves produce assimilates and directly utilizing them for structural development. On the other hand, the sharp increase in SLA at floral initiation could be that LA increased at a faster rate than accumulation of leaf mass. To allow for canopy expansion, there was active translocation of assimilates from older leaves to younger leaves (Schnyder, 1993). Photosynthetic rate of young expanding leaves is generally low and energy consumption due to the construction of structural components is high (Marchi et al.,

135

2005). At this stage the leaf is a sink as it is a net importer of photosynthates (Schnyder, 1993) and SLA is generally low. As the photosynthetic system matures and the leaf expands, requirement of respiratory energy decreases and SLA increases. At this stage the amount of assimilation increases beyond that of respiration and leaf becomes a net exporter (Marchi et al., 2005). The transition between sink and source of a leaf in relation to crop management should be assessed as a way of optimising carbon assimilation and translocation..

It was observed that increasing water availability and intercropping sorghum with cowpea had a similar effect on sorghum SLA. This was because intercropping with cowpea improved soil water availability by mulching and reducing soil water loss through bare soil evaporation (Bodner et al., 2007). Sorghum SLA decrease with either increasing water availability or intercropping with cowpea, particularly during 2014/15 growing season. This was attributed to increased photosynthetic capacity per unit area of the leaf relative to sole sorghum and sorghum grown under low water availability. Overall, increasing water availability increased stomatal conductance (g_s) and chlorophyll content index (CCI) (Chimonyo et al., under review). Stomatal conductance is proportional to rate of CO_2 fixation while an increased CCI would indicate higher energy absorption thus allowing for increased CO_2 assimilation (Yang et al., 2004). This subsequently results in heavier leaves per unit leaf area, and lower SLA. The relationship between CCI and SLA was also established by Marenco et al. (2009) and Songsri et al. (2009) in Amazonian tree species and peanuts, respectively. It could be that both traits can be used as a cheap alternative to establish photosynthetic capacity of plant leaves.

The observed changes in biomass partitioning between leaves and stems were associated with sorghum's efficiency to produce, translocate and store assimilates. Under well-watered conditions, sorghum has been observed to store assimilates in the stem. This was attributed to high stomatal conductance which allows for enhanced production of assimilates relative to when sorghum was grown under low water availability (Chimonyo et al., under review). Storing assimilates in the stem is a survival strategy which enables sorghum to mitigate unexpected perturbations as the plant can translocate the reserves to the reproductive organs so as to complete their life cycle. On the other hand, the high biomass ratio in panicles of sorghum grown under low water availability would suggest that biomass partitioning from

136

leaves to reproductive organs was favoured more than storage organs. Also, there could have been reallocation of stored assimilates from stems to panicle. This meant that the panicle became a stronger sink than the stem allowing for more assimilates to be partitioned to the panicle. Under water stress, hormones like abscisic acid (ABA), gibberellic acid (GA), and cytokines (CK) have been found to moderate sink strength (Albacete et al., 2008). For instance GA and CK increase sink strength by promoting cell division, especially at auxiliary meristems, and also paradoxically reducing plant growth rate during reproductive phase (Albacete et al., 2014). Abscisic acid was observed to optimize remobilization of assimilates from stems to the roots and panicles and retarding source strength of the canopy (Reguera et al., 2013). Phytohormones, therefore, ensure survival while at the same time conferring drought adaptation (Yang et al., 2008).

Differences observed for K values at different phenological stages of sorghum were related to LAI and the fraction of radiation intercepted. During early crop development, both LAI and fraction of radiation intercepted were low thus resulting in low K values. As the canopy expanded, LAI increased resulting in an increase in the fraction of intercepted radiation. This in turn increased the K value. Nominal differences observed for K value for the different crop species at flag leaf appearance stage of sorghum would suggest that species specific architectural components, that is, LAI, leaf angle distribution, leaf dispersion and branch orientation, balanced out the value. Change in one of the mentioned factor(s) resulted in an inversely proportional change in another factor(s). The similarities are, however, misleading because K value were derived from an empirical equation used to represent a trait that is complex in nature. The three crop species have their own morphology and morphogenesis and differ for spatial distribution of LAI and leaf geometrical features. Also, they differ in terms of leaf dispersion. Therefore, one of the assumptions used with the Beer–Lambert law is that leaf distribution within the layers is homogenous (Wind & Szymanski, 2002) might not be met.

The differences observed for IPAR between sole sorghum and sorghum intercropped with either cowpea or bottle gourd could be attributed to underestimation of IPAR for intercropped sorghum by the modified Beer–Lambert equation. The equation assumes that leaf area is distributed evenly along the height of the sorghum stem. This might have resulted in an over

estimation of the *K* value and an underestimation of intercepted radiation. Leaf geometry within sorghum is such that more leaves are clumped in the top half of the plant in a conical manner to increase radiation interception (Van Gardingen et al., 1999). To improve estimations of IPAR, clumping factor can be considered in the calculation (Breda, 2003). There was good association between water availability and IPAR. For sorghum grown under deficit irrigation, high IPAR was observed in comparison to that which was grown under FI and RF conditions. The trend was consistent with observed results of soil water content (DI>RF>FI) but were inconsistent to results of LAI. Under DI, withdrawal of water at vegetative stage is supposed to supress canopy expansion resulting in a reduction in IPAR (Farré & Faci, 2006). This would insinuate a reduction in canopy size also means that less radiation is intercepted (Samperio et al., 2015). Since IPAR for sorghum intercropped with either cowpea or bottle gourd was consistently high, especially under limited water conditions, results suggest that IPAR can be improved with intercropping without added cost of irrigation. These results are consistent with those observed by Tsubo et al. (2001) and Zhang et al. (2008) who also observed an increase in radiation interception with maize/bean and wheat/cotton intercrop systems under low water availability.

Radiation use efficiency (RUE) is an important biomass determinant that has been used to develop simple crop models such as those employed by Monteith and Moss (1977) and also in mechanistic models such as APSIM (McCown et al., 1996). Radiation use efficiency can be increased by enhancing yield or biomass output with a fixed IPAR or reducing IPAR with a fixed output. Radiation use efficiency derived from biomass (RUEb) increased with each consecutive phenological stage and with increase in water availability. The improvements were due to high rate of biomass accumulation relative to the rate of increase in IPAR. Although intercropping resulted in an overall improvement in RUEg, these were inconsistent across the growing season and water regimes. The high RUE observed during 2013/14 relative to 2014/15 growing season could be due to the low IPAR observed. During 2013/14 growing season, LAI was low and this resulted in a reduction in the amount of IPAR. Increasing availability of water increased LAI under intercropping, however, this did not always result in improved RUEg. It could be that under DI, the observed decrease in RUE$_g$ for sorghum – cowpea intercrop system was attributed to the low yield for cowpea and high IPAR for the intercrop system.

Conclusions and recommendations

Intercropping sorghum with either cowpea or bottle gourd did not have any negative effect on SLA, LAI and biomass production and partitioning of sorghum. Under limited water availability, intercropping sorghum with either cowpea or bottle gourd resulted in more of a facilitative interaction with respect to water and radiation from a leaf physiological basis. Cowpea and bottle gourd were able to improve soil water availability by minimizing soil evaporation. Intercropping this cowpea allowed for enhanced soil water capture from the soil profile which resulted in improvements in SLA. In this study, LAI was a useful trait in assessing IPAR in that they were closely associated. To improve the estimation of IPAR for intercropped sorghum, a clumping factor must be considered in the calculation. Under RF conditions, intercropping improved overall radiation capture and RUE of a sorghum cropping system. Overall, RUE (biomass and yield) for sorghum – bottle gourd intercrop system was 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. From a cropping systems standpoint, intercropping should be recommended for semi – and arid environments since it enhances soil water availability resulting in improved RUE

Acknowledgements

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CHAPTER 6

SIMULATING YIELD AND WATER USE OF A SORGHUM–COWPEA INTERCROP USING APSIM

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Abstract

Crop simulation models such as APSIM can be used to increase available information OM intercropping with regards to management under water scarcity. However its practical use in managing intercrop systems is very limited. Growth, yield and crop water use (ET) of a sorghum–cowpea intercrop system were evaluated using APSIM and data from field experiments conducted at Ukulinga Research Farm, South Africa over two seasons (2013/14 and 2014/15). Weather and soil data were observed *in situ* and input into APSIM. Data from optimum experiments (2013/14) was used for local adaptation of APSIM. Thereafter, the model was tested using data obtained from 2014/15 under various water management strategies [rainfed (RF), deficit (DI) and full irrigation (FI)]. Model simulations were evaluated using observed data for phenology, leaf number, leaf area index (LAI), biomass, yield, ET and water use efficiency (WUE). Model performance was assessed using R^2, root mean squared error (RMSE) and its components (RMSEs and RMSEu) and the d-index. The model simulated phenology satisfactorily for sorghum (R^2 = 0.98, RMSE = 6.62 days, d – index = 0.99) and cowpea (R^2 = 0.86, RMSE = 13.67 days, d – index = 0.99) across different water regimes. The model underestimated LAI (36.98%); this was associated with defoliation of crop canopy due to hail damage. Satisfactory simulations (RMSE RF = 145.38 kg ha^{-1} < DI = 37.38 kg ha^{-1} < FI = 35.99 kg ha^{-1}) of sorghum yield (RF = 953.63 kg ha^{-1} < DI = 1079.32 kg ha^{-1} < FI = 1082.52 kg ha^{-1}) with improvements of water availability were observed. The model also gave satisfactory (RMSE RF = 3.06 kg mm^{-1} ha^{-1} >DI = 1.97 kg mm^{-1} ha^{-1} >FI = 1.66 kg mm^{-1} ha^{-1}) simulations of system WUE across the water regimes [RF = 17.54 kg mm^{-1} ha^{-1} >DI = 16.43 kg mm^{-1} ha^{-1} >FI = 16.75 kg mm^{-1} ha^{-1}]. The APSIM model was able to simulate growth, yield and WU of an intercrop system under varying water regimes, However, it is still limited with regards to rainfed conditions since it overestimated biomass (6.25%), yield (14.93%) and WU (7.29%) and under estimated WUEb (-14.86%). APSIM can still be used to determine best management practise for intercropping under water scarce environments.

Keywords: biomass; crop model; leaf area index; water use efficiency

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 and variability simulations indicate an increase in the occurrence and severity of weather extremes such as drought and flooding within the region (Connolly-Boutin and Smit, 2015). This will increase the vulnerability of an already weak agricultural system (Connolly-Boutin and Smit, 2015). Production uncertainty remains a fundamental constraint to many stakeholders who often over- or under-estimate the impacts of climate change and variability (Cooper et al., 2008). Notwithstanding this, these uncertainties have increased pressure on current rainfed systems to improve productivity in an efficient and sustainable manner so as to meet current and future food requirements. In this regard, intercropping has emerged as a suitable approach for sustainable intensification of agriculture, especially under water limited conditions (Cooper et al., 2008). 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 variegated 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 studying 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) have since been employed (Boote et al., 1996) as tools for generating useful data for assessing current and future productivity. Crop simulation models were developed to improve understanding of crop responses to environment and management practices (Basso et al., 2013) at different hierarchical levels (cellular – farm system levels). They have been used extensively to aid formulation of national and regional policies for production and risk management of major crops across different cropping systems, including rainfed systems (Lambin et al., 2000). Therefore, CSM can also be used to increase available information for intercropping with regards to management and environment.

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). Robertson et al. (2004) evaluated lucerne – wheat/canola intercrop systems with APSIM and concluded that competition for water and solar radiation was well–simulated. Dimes et al. (2011) used APSIM for assessing maize and bean intercrop systems in southern Africa and indicated that better growth descriptors were still required for low yielding bean varieties. Harris et al. (2008) observed satisfactory model performance for APSIM for lucerne – cereal intercrop and concluded that it could be used for management intervention on companion crop performance, thus identifying the circumstances under which the practice might be feasible. Poor performance of APSIM in predicting growth of wheat - field pea intercrop systems was attributed to different sowing dates but conformed to the competition 'canopy' module that partitioned more resources to the established component crop (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 inadequate literature that support 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 all continents as it has the ability to simulate the response of a range of crops to different climates and soils under alternative management options (Carberry et al., 1999). Its efficiency to simulate crop responses to climatic and management variations has been derived from rigorous testing. Therefore, the efficiency of APSIM to simulate intercrop system also requires such rigour so as 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 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.

Materials and methods

Description of study area

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 (2012/13 and 2013/14). For full description of experimental site refer to Chimonyo et al. (in press).

Experimental design

The field experiment was set up as a split–plot arrangement with sub–plots nested in a randomised complete block design within the main plot, 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 (in press). All cultural practices (weeding, fertilizer application rates and pest management) were done in line with best management practices.

Model description

The Agriculture Production systems SIMulator (APSIM) is a crop simulation model created in response to the need to improve planning and forecasts for crop production under different climatic, soil and management conditions (Carberry et al., 1996). It is a point scale model and simulates production outputs of the management of a single homogenous field over a specified time period (McCown et al., 1996). The model comprises ten 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, soil pH, erosion) and management (tillage, irrigation, fertilization). Communication between the modules is via the APSIM engine. The engine transmits information between the modules following a standard protocol that allows modules to be plugged in or pulled out, all dependent on the specifications of the task required. The APSIM model is able to 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.

APSIM – Canopy 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. The arbitrator determines the amount of solar radiation intercepted each component of the intercrop using LAI extinction coefficient and height for each crop. On a daily basis, the module finds the number of crops in the simulation and their canopy heights (Keating et al., 2003). Thus, there are as many layers as canopies. Each layer in turn is taken from the top, in the combined canopy, to get the combined value (green + dead) of the canopies present in that layer. The fraction of solar radiation transmitted out of the bottom of that layer can be calculated, and this translates to the fraction entering the layer below. The total radiation intercepted in a layer is divided amongst the canopies occupying the layer, being done on the basis of each canopy. This approach ignores the possibility of different LAI distributions within a layer. Leaf area index is distributed with height in the canopy using normalized height and integration of a function to the power of 5. This results in 47% of the leaf area in the top 10% of height, 27% in the next 10%, 15% in the next 10%, and so on (Keating et al., 2003). Arbitration for water and nitrogen uptake is done on the

151

basis of 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.

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

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 parameters obtained and used to develop the MET file were maximum (T_{max}) and minimum (T_{min}) 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 hail storms 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 [clay, loam or sand], fertility

[low (LF) - < 0.7% soil organic carbon content (SOC); medium (MF) – between 0.7 – 1.2% SOC; high (HF) – > 1.2% SOC] and rooting depth [shallow (< 90 cm), medium (90 – 150 cm) and deep (> 150 cm)]. 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 = 7.3%) 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 1).

The soil/root water extraction coefficient and root penetration parameter (XF, 0 − 1 multiplier on the rate of root growth) for sorghum and cowpea were set to default values of 0.08 (KL, d − 1) and 0.08 and 1.00, respectively, 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 second stage soil evaporative coefficient CONA (3 mm d $^{-0.5}$) was estimated from soil texture (Littleboy et al., 1999). Values of CONA and U were input in to the model so as to improve simulation of water lost through bare soil evaporation. The rate at which water drains from, 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)

Table 4: Soil water properties at different depths for soil at the experimental site at UKZN– Ukulinga Research farm.

Depth (m)	TX[8]	BD[1] (g m^{-3})	Airdry[2]	LL15[3]	DUL[4] (mm m^{-1})	TAW[5]	SAT[6]	KS[7]	OM[9] %
0 – 0.10	Clay	1.29	0.34	21.04	33.54	12.5	48.66	20.9	7.3
0.10 – 0.30	Clay	1.47	0.69	47.61	69.94	24.63	97.89	18.18	2.6
0.30 – 0.60	Clay	1.4	2.39	79.23	110.42	34.13	149.83	13.92	0.8
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 OM% – Percentage composition of ogarnic matter

APSIM-Crop modules: To adapt sorghum and cowpea files, crop coefficients were developed based on observed data on crop traits collected from plots of sole sorghum and cowpea grown under full irrigation. The observed traits included phenology, leaf number and leaf appearance rate, as well as, radiation use efficiency. Data on biomass accumulation, final yield, and cumulative WU and WUE were also collected for the purpose of evaluating model performance.

Phenological data observed for sorghum and cowpea included end of juvenile stage, floral initiation, flowering, length 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):

$$GDD = \left[\frac{T_{max} + T_{min}}{2} \right] - T_{base} \qquad \text{Equation 12}$$

where: GDD = growing degree days (°Cd), Tmax and Tmin = maximum and minimum

temperatures, respectively, and Tbase = base temperature. If Tmax < Tbase then Tmax = T

base and if Tmin < Tbase then Tmin = Tbase.

End of juvenile stage was marked by the formation of the first true leaf/trifoliate (fully expanded and exposed), with a leaf collar in the case of sorghum. End of juvenile stage was observed from sowing to when more than 50% of plants in the experimental plots had formed the first true leaf. Time to end of juvenile stage for sorghum and cowpea was observed as 120 °Cd and this was used as an input for coefficient tt_emerg_to_endjuv within phenology description of the sorghum and cowpea cultivar in the respective crop files (Table 2). Floral initiation is a period when reproductive structures of the plants start developing. Time to floral initiation for sorghum was observed as the time from emergence to the appearance of a bulge/swelling at the base of the stem for sorghum. Time to floral initiation for sorghum cultivars was observed as 260 °Cd. Time to end of juvenile stage (tt_emerg_to_endjuv) and time to floral initiation were then used to calculate sorghum crop coefficient tt_endjuv_to_init (time between end of juvenile stage to floral initiation) within the sorghum crop files (Table 2). Coefficient tt_endjuv_to_init was calculated as 140 °Cd and this was input in the phenology description of the sorghum cultivar within the crop file (Table 2). For cowpea, time to floral initiation was taken as the time from appearance of peduncles from leaf axils. For cowpea, the observed coefficient endjuv_to_init was similar to model default, therefore this coefficient was not changed. Flag leaf is the last leaf that appears within the whorl of the sorghum plant. Time to appearance of the flag leaf was observed as the time between sowing and the appearance of the last leaf that appears within the whorl of the sorghum plant. Flowering for sorghum and cowpea was defined as when 50% or more of florets on the panicle and peduncles, respectively, start releasing pollen (anthesis). Time to flowering was observed as the time between planting and flowering. Time to flowering (965 °Cd) and time to appearance of flag leaf (786 °Cd) was used to calculate sorghum crop coefficient flag_to_flower The sorghum coefficient tt_flag_to_flower (179 °Cd) was calculated as the time interval between time to appearance of flag leaf and flowering (Table 2). Similarly, for cowpea, the observed coefficient tt_init_to_flower was similar to model default, therefore the default values were used. Physiological maturity is attained when the dark layer forms at the point of attachment of the grain to panicle or pod. For both sorghum and cowpea, the time

155

interval between flowering and maturation was similar to model default values, therefore the default values were used.

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 adjusted accordingly (Table 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. Leaf appearance rate was calculated by regressing number of leaves that were visible on thermal time (base $8°C$) from emergence. Phyllochron ($°Cd$ $leaf^{-1}$) is the reciprocal of leaf appearance rate (Clerget et al., 2008). 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 2).

Table 5: Modification of crop coefficients based on observed results from 2013/14 growing season.

Parameter description	Coefficient name	Value
Base temperature for sorghum and cowpea	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}) (Sorghum)	RUE	1.15
Radiation use efficiency (g (biomass) MJ^{-1}) (Cowpea)	RUE	1.19
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

*traits with asterisk represent default values used in APSIM – sorghum module while those without were observed values.** value obtained from Hodges (1990)

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 $^{-1}$). Routine measurements of intercepted photosynthetically active radiation (IPAR) were taken for sole crops of sorghum and cowpea at midday using the AccuPAR LP80 (Decagon Devices, USA). Thereafter, destructive sampling of sorghum and cowpea plants was done to determine biomass accumulation (kg ha^{-1}). Sampled plants were oven dried at 85°C until constant mass was attained. Radiation use efficiency at each sampling interval was then calculated as

$$RUE = \frac{B}{IPAR}(kg\ MJ\ PAR\ ha^{-1}) \qquad\qquad \text{Equation 2}$$

where: RUE = Radiation use efficiency (kg MJ PAR^{-1} ha^{-1}),

Y = the economic yield (kg ha^{-1}), B = biomass (kg ha^{-1}) and IPAR = Intercepted PAR.

Observed RUE values for sorghum (1.25 g MJ $^{-1}$) and cowpea (1.65 g MJ $^{-1}$) were input within 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 S.E. (±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 2).

At harvest maturity each component crop across the different treatments was harvested for yield determination. At harvest, above ground plant matter of six representative plants of sorghum and cowpea were taken and reproductive organs processed for yield (kg ha^{-1}).

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 – ΔSWC $\qquad\qquad$ Equation 3

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 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.

APSIM – *Irrigation:* To simulate irrigation, irrigation events within the model were set to corresponded to dates of actual irrigation events that occurred within field experiments. Observed irrigation applied per event for the field experiment was calculated to be on average 12 mm ± 5.5 mm (SD). Irrigation amount within the irrigation node 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 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 soil water content at planting. For the 2013/14 planting season, 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 upto 15 days after 2013/14 crop establishment. Soil water content at planting was modelled to be 31% and this value was inputted in to the local adaptation simulation as initial soil water content. During 2014/15 planting season, before planting irrigation was applied so as to recharge the soil back to field capacity (DUL). Within the initial soil water node 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 node was used to represent management options within the simulation. Within the node, sowing date was set to fall in between 13 – 20 January, 2014 for model adaptation

159

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 not added in cowpea sowing node.

Model evaluation

Data collected during the 2013/14 growing season was used for local adaptation of APSIM sorghum–cowpea model. Data collected during the 2014/15 growing season was used to test the performance of the model.

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:

$$WUEy/b = \frac{Y/B}{WU} (kg\ mm^{-1}\ ha^{-1})$$
<div align="right">Equation 4</div>

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

Correlation of determination R^2: Correlation of determination, R^2, describes goodness of fit between O and S. Values of R^2 range between 0 and 1 with high values indicating less error

variance. The interpretation of R^2 is *n* dependent. Low values are only acceptable if *n* is huge. Where is *n* is low (e.g. *n* < 10), high values (R^2 > 0.85) would be acceptable and vice versa. The disadvantage to using R^2 values is that they are over sensitive to outliers and insensitive to additive and proportional differences between S and O.

To indicate how much a fitted linear regression between simulated and observed deviated from the ideal S = O, the bias correction factor was visually depicted by plotting a line (*x* = *y*) that passed through the origin (0, 0).

Systematic and unsystematic components of the root mean squared error (RMSEs and RMSEu, respectively) as well as the total root mean squared error (RMSE): Root mean squared error is a commonly used error index for statistics (Willmott, 1981). The use of RMSE and its systematic (RMSEs) and unsystematic (RMSEu) derivatives was proposed by Willmott (1981) to measure model performance. For interpretation of results, RMSEs should approach zero, while RMSEu should approach RMSE in order for a model's performance to be considered as good. The relationship between RMSEu and RMSE (RSMEu/RSME) was also expressed as a percentage. Calculations of RMSE, RMSEs and RMSEu are as follows:

$$RMSE_S = \left[n^{-1} \sum_{i=1}^{n} (\hat{S}_i - O_i)^2 \right]^{0.5} \hspace{3cm} \textbf{Equation 5}$$

$$RMSE_U = \left[n^{-1} \sum_{i=1}^{n} (\hat{S}_i - S_i)^2 \right]^{0.5} \hspace{3cm} \textbf{Equation 6}$$

$$RMSE = (RMSE_S + RMSE_U)^{0.5} \hspace{3cm} \textbf{Equation 7}$$

where, *n* is the number of observations, $\hat{S}i$ is derived from $\hat{S}i = a + b.Oi$ where a and b are the intercept and slope respectively, of a least regression between the simulated (dependent variable) and observed (independent variable) values.

According to Willmott (1981), information obtained for RMSE, RMSEs and RMSEu is often complimented by the d-index.

Index of agreement (D – index): Index of agreement is a standardized measure of the degree of model simulation error and varies between 0 (no agreement) and 1 (perfect agreement). It is computed as follows:

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum[|s'_i| + |o'_i|]^2}, 0 \leq d \leq 1 \qquad \qquad \textbf{Equation 8}$$

where, S' =Si – Ō and Ōi = Oi – Ō whereby Ō is the observed mean.

The index of agreement represents the ratio between the mean square error (MSE) and potential error (Willmott, 1981). In this instance the potential error is the sum of the squared absolute values to the mean observed value. The index can detect additive and proportional differences in the observed and simulated means of variance although it too is sensitive to extreme values due to the squared differences (Legates and Jr, 1999).
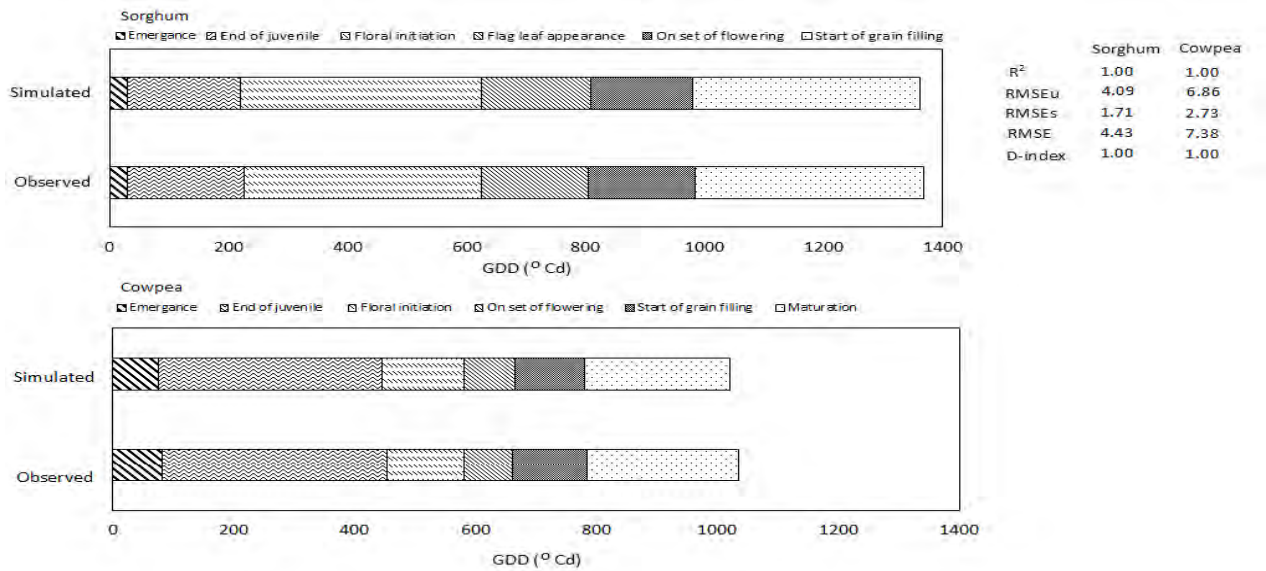
Local adaptation

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 (R^2 = 1.00; RMSE = 4.43 °Cd, d – index = 1.00). The RMSEu (4.09 °Cd) was shown to approach RMSE, although there was a 7.67% difference (Fig. 1). The RMSEs (1.71 °Cd) approached zero, therefore model performance was deemed as good. Model simulations for phenology for cowpea were also satisfactory (R^2 = 1.00; RMSE = 7.38 °Cd, d – index = 1.00) (Fig. 1). The RMSEu (6.86 °Cd) was shown to approach RMSE, although there was a 7.04% difference. The RMSEs (2.73 °Cd) approached zero, therefore, model performance was deemed good.

Plant phenology is a critical component for adaptation especially under resource limitation. After the adjustments of crop specific coefficients, the model's ability to accurately simulate phenology for both cowpea and sorghum was improved. APSIM crop files has its own default cultivars for different maturity classes. However, cultivars described within the crop files do not always represent accurately the wide genetic diversity that exists for sorghum and cowpea. These results are contrary to those by Ncube et al. (2009) who observed good simulations of phenology from existing crop cultivars of sorghum and cowpea within APSIM. On the other hand, results of the current study are similar to those observed by Potgieter et al. (2005) and Msongaleli et al. (2014) who observed improvements in model simulation of phenology after local adaptation of crop coefficients. In cases were new

cultivars are being modelled, local adaptation should always be considered so as to improve model simulation.
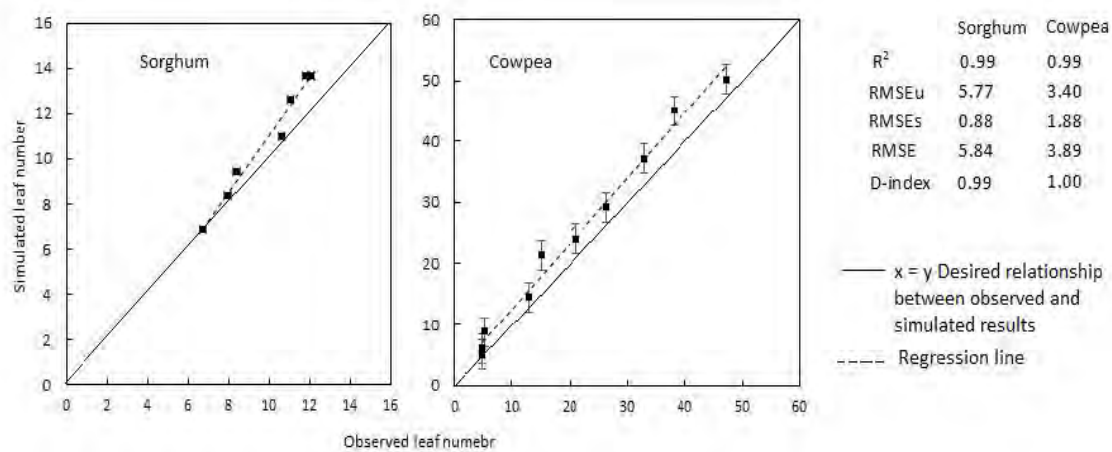

Figure 1. Local adaptation of APSIM model for sorghum and cowpea showing observed and simulated values for phenology and statistical output for its evaluation.

Leaf number

Model simulation for leaf number for sorghum was satisfactory (R^2 = 0.99; RMSE = 5.84, d – index = 0.99) although the model over estimated by one leaf. The RMSEu (5.77) was shown to approach RMSE and the difference was 1.19% (Fig. 2). The RMSEs (0.88) approached zero, therefore the model performance was deemed as good. Model simulations for leaf number for cowpea were also satisfactory (R^2 = 0.99; RMSE = 3.89, d – index = 1.00) (Fig. 2) though the model over estimated by an average of three leaves. The RMSEu (3.40) was shown to approach RMSE with a 12.59% difference. The RMSEs (1.88) approached zero, therefore, model performance was deemed good.

163

Adjustments of leaf development rates (rate 1 and 2) (Table 1) for sorghum ensured that the model was able to capture the relatively small number of leaves for the cultivar simulated. Final leaves developed and rate of leaf development in sorghum are strongly related with phenology i.e. floral initiation and rate of leaf primordia development. The good simulation of floral initiation and adjustments of leaf development rates, therefore, improved accuracy of simulation of leaf number by the model. 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. 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 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 (±).

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 (0.56 and 0.22, respectively) while RMSE (0.12 and 0.24, respectively) was observed to be high (Fig. 3). Although RMSEs was approaching zero (0.07 and 0.17, respectively) it was considered high (RMSEs > 0.5 RMSE)

164

and the model's performance with respect to simulation of LAI was deemed poor (Fig. 3). Contrary to results of R^2 and RMSE and its components, d-index for both sorghum (0.99) and cowpea (0.99) was high. However, the d-index is not reliable in this case since the relation of observed and simulated data was asymmetric; that is, the rate of increase for observed LAI was not proportional to that of simulated LAI. The observed low agreement between observed and simulated LAI could be attributed to the model's inability to capture defoliation of leaves by hail storm that occurred earlier in the season which reduced observed LAI relative to simulated. On the other hand, the APSIM model has been observed to perform poorly for predications of LAI. For instance, Asseng et al. (1998) observed $R^2 = 0.59$ for wheat while Hammer et al. (2010) observed an $R^2 = 0.86$ 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 ($R^2 > 0.85$) would be acceptable and vice versa.

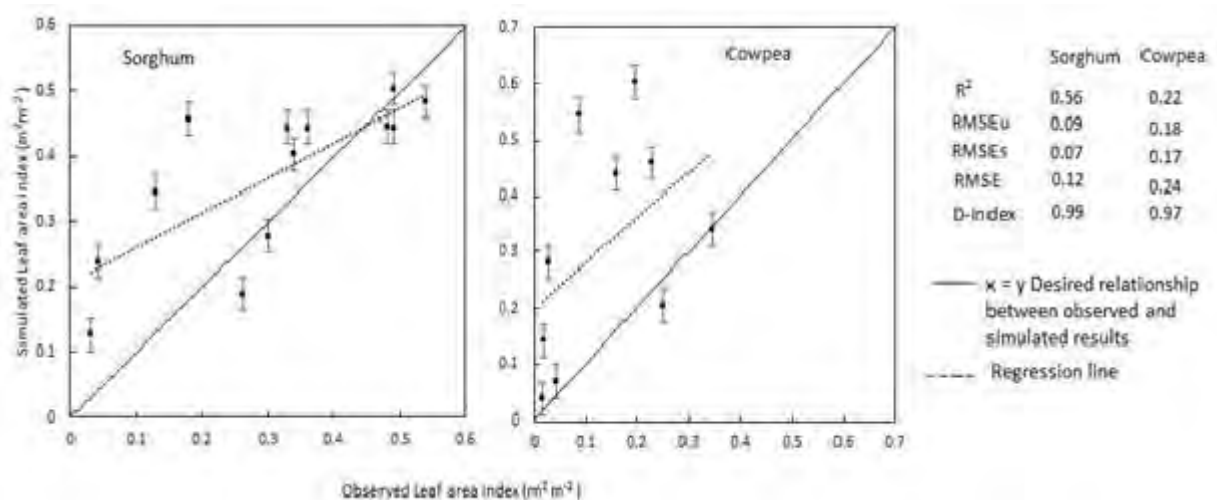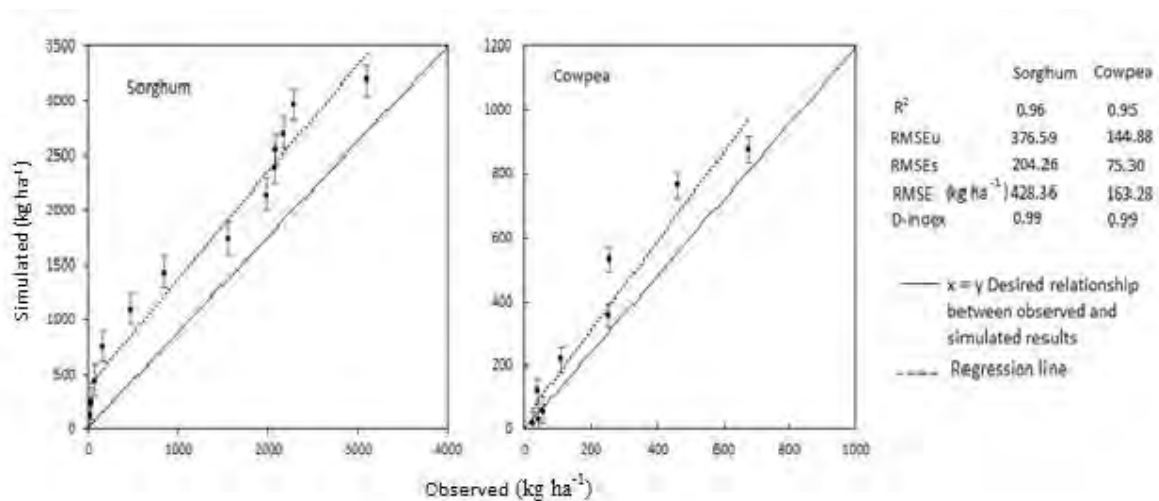

Figure 3. Local adaptation of APSIM model for sorghum and cowpea showing observed and simulated values for leaf area index (m^2 m^{-2}) and statistical output for its evaluation. Vertical bars on observed data represent standard error ($\pm$).

Biomass, yield, WU and WUE

The model simulated sorghum biomass (3188.15 kg ha^{-1}) reasonably well (R^2 = 0.96; RMSE = 428.36 kg ha^{-1}; d – index = 0.99). The RMSEu (376.59 kg ha^{-1}) was shown to be approaching RMSE with a 11.26% difference. The RMSEs (204.26 kg ha^{-1}) was approaching zero, therefore the model fit could be deemed good. For cowpea, the model simulation for biomass (848.63 kg ha^{-1}) was also a good (R^2 = 0.95; RMSE = 163.28 kg ha^{-1}while d – index = also 0.99). The RMSEu (144.88 kg ha^{-1}) was shown to approach RMSE while the RMSEs (75.30 kg ha^{-1}) approached zero (Fig. 4). This was despite the poor simulation of LAI. The good model performance could be attributed to the fact that biomass is calculated as a derivative of RUE. The use of calculated RUE values for both cowpea and sorghum increased the accuracy and stability of biomass. Therefore, the crop coefficient RUE is an important parameter in accurately simulating biomass production.

Figure 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 (±).

Model simulation for yield for sorghum was satisfactory as indicative of the low RMSE value of 82.73 kg ha^{-1} and a difference of 7.17% from observed yield (Table 3). This was in

line with results of simulated phenology and biomass. On the other hand, model simulation for cowpea yield was poor (RMSE = 44.80 kg ha^{-1}) with an overestimation of 31.03% (Table 3). The overestimation of cowpea yield by the model could be attributed to the carry over error brought about by overestimation of LAI and biomass such that more biomass was produced and partitioned to yield. The model's response of yield to LAI, biomass and yield are similar to those observed by Cheeroo-Nayamuth et al., (2000) and Moeller et al. (2014). Conversely, the model was able to explain 68.97% of yield observed under field conditions (Table 3). This would suggest that other than intercropping and its possible effect on resource availability, cowpea succumbed to other yield reducing factor(s), such as poor rhizobium activity, that could not be captured by the model. With regards to this, the model can be used to assess yield gaps could have affected sorghum–cowpea intercrop system.

Good simulations of crop water use (ET) by the model were also observed with a RMSE value of 33.31 mm; however, there was an over-estimation by 7.31% (Table 3). Similar to biomass simulation, overestimation of ET could also be attributed to over estimations of LAI (Table 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 overestimation 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 reduced soil surface evaporation within the intercrop system.

The WUE calculated on the basis of model simulated yield and biomass of the system showed very good fit (0.34 and 2.11 kg mm^{-1} ha^{-1}, respectively) for simulated and observed results (Table 3). The WUEy difference (2.08%) between the observed and simulated for yield was within a reasonable margin (Table 3). The large differences (14.80%) observed for WUEb can be attributed to overestimation 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.

Table 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.

		Observed	**Simulated**	**RMSE**	**% Difference**
Crop water use (mm)		307.37	329.86	22.49	7.31
Yield (kg ha^{-1})	Sorghum	1156.63	1239.36	82.73	7.17
	Cowpea	145.00	189.80	44.80	31.0
WUEy[1] (kg mm^{-1} ha^{-1})		4.23	4.33	0.34	2.08
WUEb[2] (kg mm^{-1} ha^{-1})		14.25	16.36	2.11	14.80

[1]WUEy – Grain water use efficiency; [2]WUEb – Biomass water use efficiency.

Model testing

Phenology

Similar to observed results from field experiment where water regime did not affect time to phenological event for sorghum and cowpea, model simulated phenological events were not affect by differences in water availability. Conversely, model simulations for phenology for sorghum and cowpea under different water regimes were very good (R^2 = 1.00 and 1.00; RMSE = 2.46 and 5.24 °Cd, d – index = 1.00 and 1.00, respectively) (Fig. 5). The RMSEu (2.12 and 4.77 °Cd) was shown to approach RMSE, although there was a 13.82 and 8.96% difference. The RMSEs (1.23 and 2.16 °Cd, respectively) was approaching zero (Fig. 5). The observed RMSE for the different water regimes was consistent with observed results of local adaptation evaluation indicating model stability and robustness.

The ability to accurately simulate phenology is critical for crop production as it has huge consequences to crop management practices and crop cultivar choices. 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 ensures that 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 crop responses to varying water management strategies.
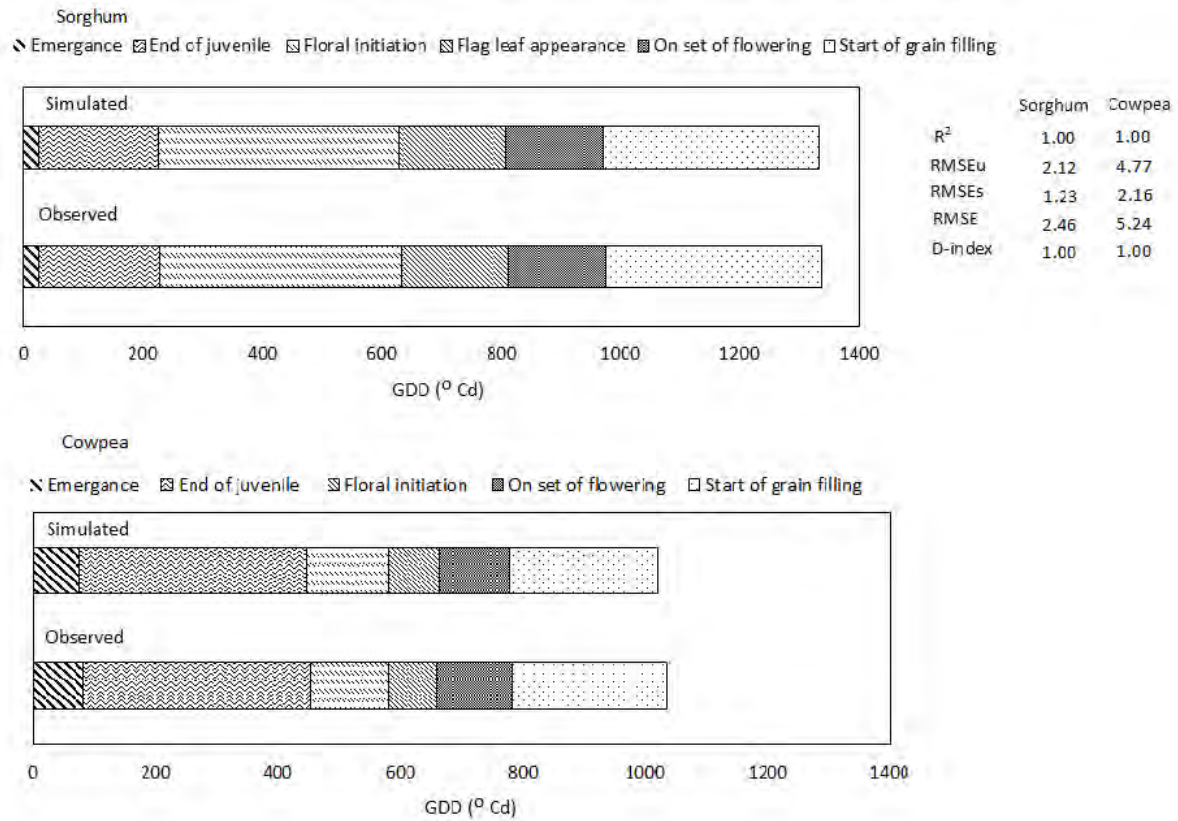
Figure 5. Comparison of observed and simulated values for sorghum and cowpea phenology and statistical output for its evaluation.

Leaf number

Model simulations for leaf number for sorghum under FI were poor ($R^2 = 0.71$; RMSE = 2.94, d – index = 0.99). The RMSEu (2.23) was shown to approach RMSE, although there was a 24.23% difference (Fig. 6). Simulation of leaf number of sorghum under DI was satisfactory ($R^2 = 0.81$; RMSE = 2.79, d – index = 0.99). The RMSEu under DI (2.34) was shown to approach RMSE, although there was a 16.12 % difference while RMSEs (1.92) was high (RMSEs = 0.5 RMSE) (Fig. 6). Under RF conditions, model simulation for leaf number

169

was also poor (R^2 = 0.61; RMSE = 2.80, d – index = 0.99). Although the RMSEu under RF (2.06) was shown to approach RMSE, there was a 26.12 % difference while RMSEs (1.53) was high (RMSEs = 0.5 RMSE) (Fig.6). For cowpea, model simulation for leaf number under FI was very good (R^2 = 0.97; RMSE = 6.53, d – index = 1.00). The RMSEu (5.59) was shown to approach RMSE, although there was a 16.81% difference while RMSEs (1.90) was approaching zero (Fig. 6). Similarly, simulations of leaf number for cowpea under DI and RF conditions were also satisfactory (R^2 = 0.86 and 0.86; RMSE = 12.02 and 10.62, d – index = 0.99 and 0.99, respectively). The RMSEu under DI (11.94) and RF (9.97) was shown to approach RMSE, although there was a 0.6 and 6.51% difference, respectively; while RMSEs (1.45 and 3.67, respectively) was approaching zero (Fig. 6).

The model did not show a good fit for sorghum for leaf number across the water regimes (Fig. 5). The model over-estimated leaf number for sorghum for the three water regimes. In this study substantial defoliation of plants in the field experiment occurred due to hail damage at 79 DAP (718.87 °Cd) resulting in significant loss in leaves. Before the storm, there was generally good agreement between observed and simulated results. The model was unable to capture hail damage thus resulting in overestimation of leaves for sorghum. Although APSIM was able to recognise the hail storm event as heavy rainfall, effect of high rainfall intensity and hail storm could not be translated onto sorghum canopy, the over-story. Therefore, leaf number simulated represents the potential leaf number of sorghum. On the other hand, the good performance of the model under FI conditions could be because model adaptation was done using dataset obtained under full irrigation. This would suggest that there is still need to improve model adaptation so as to improve response across different water regimes. Although leaf number of cowpea plants within the field experiment were also affected by hail, they managed to regrow most of their leaves due to the presence of secondary branch nodes on primary branches. With the absence of the hail storm, model output would suggest that there was an underestimation of leaf number for cowpea. With the increase in occurrence of extreme weather events such as hail storms, 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.
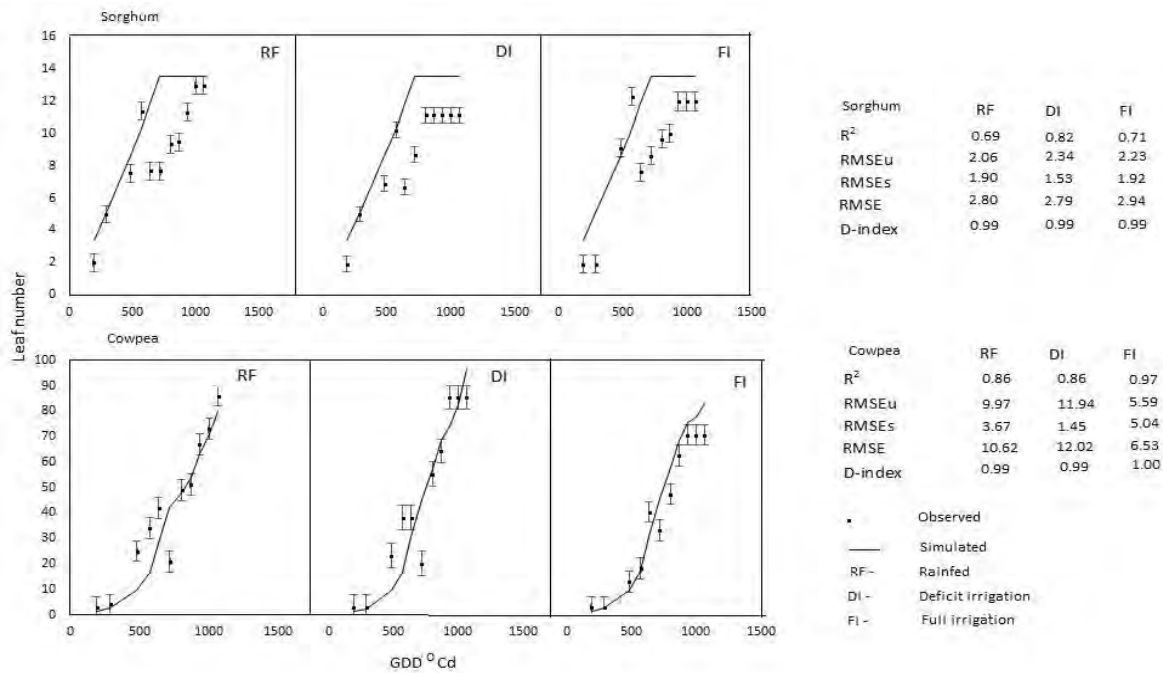
Figure 6. Comparison of observed and simulated values for sorghum and cowpea leaf number (kg ha^{-1}) under different water regimes and statistical output for its evaluation. Vertical bars on observed data represent standard error ($\pm$).

Leaf area index

Model simulations of LAI for sorghum under FI were poor ($R^2 = 0.68$; RMSE = 0.19 m^2 m^{-2}, d – index = 1.00). Although the RMSEu (0.15 m^2 m^{-2}) was shown to approach RMSE, there was a 21.05% difference while RMSEs (0.11 m^2 m^{-2}) was high (RMSEs > 0.5RMSE) (Fig. 7). Simulation of LAI of sorghum under DI was satisfactory ($R^2 = 0.71$; RMSE = 0.19 m^2 m^{-2}, d – index = 1.00). The RMSEu under DI (0.17 m^2 m^{-2}) was shown to approach RMSE, although there was a 10.52% difference while RMSEs (0.09 m^2 m^{-2}) was approaching zero (Fig. 7). Under RF conditions, model simulation for LAI was satisfactory ($R^2 = 0.75$; RMSE = 0.39 m^2 m^{-2}, d – index = 1.00). The RMSEu under RF (0.38 m^2 m^{-2}) was shown to approach RMSE, although there was a 2.56% difference while RMSEs (0.09 m^2 m^{-2}) was approaching zero (Fig. 7).For cowpea, model simulations for LAI under FI were satisfactory ($R^2 = 0.76$; RMSE = 0.21 m^2 m^{-2}, d – index = 0.99). The RMSEu (0.29 m^2 m^{-2}) was shown to approach

171

RMSE, although there was a 38.09% difference while RMSEs (0.07 $m^2 m^{-2}$) was approaching zero (Fig. 7). Simulation of LAI of cowpea under DI was satisfactory ($R^2 = 0.61$; RMSE = 0.25 $m^2 m^{-2}$, d – index = 0.99). The RMSEu under DI (0.25 $m^2 m^{-2}$) was equal to RMSE (Fig. 7) while RMSEs (0.03 $m^2 m^{-2}$) was approaching zero. Under RF conditions, model simulation for LAI was also good ($R^2 = 0.75$; RMSE = 0.39 $m^2 m^{-2}$, d – index = 1.00). The RMSEu under RF (0.38 $m^2 m^{-2}$) was shown to approach RMSE, although there was a 2.56% difference while RMSEs (0.06 $m^2 m^{-2}$) was approaching zero (Fig. 7).

Similar to leaf number, the model did not always show a good fit for sorghum for leaf area index (LAI) across the water regimes (Fig. 7). Unlike leaf number, the model under-estimated LAI for sorghum for all the three water regimes from floral initiation (Fig. 7). During local adaptation of the model, tillering, which often precedes after floral initiation, was not observed in the field experiment and this was in agreement with simulated results. Under field conditions, tillering is a sensitive parameter, affected by soil moisture and photoperiod (Kim et al., 2010). Late planting for experiment established during the 2013/14 resulted in photoperiods of less than 12hrs 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. However, the margin of error between the observed and simulated results could be deemed satisfactory since RMSE were generally low, RMSEs were approaching 0 and d - index were high. 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-simulation of cowpea LAI. These results are consistent to results observed by Garrido et al. (2013) and Brown et al. (2014) who also observe an initial under-estimation of wheat LAI simulations in APSIM.

This would suggest that for improved model simulations, additional routines which allow switching from sigmoid to other functions should be incorporated into plant modules.

Figure 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 (±).
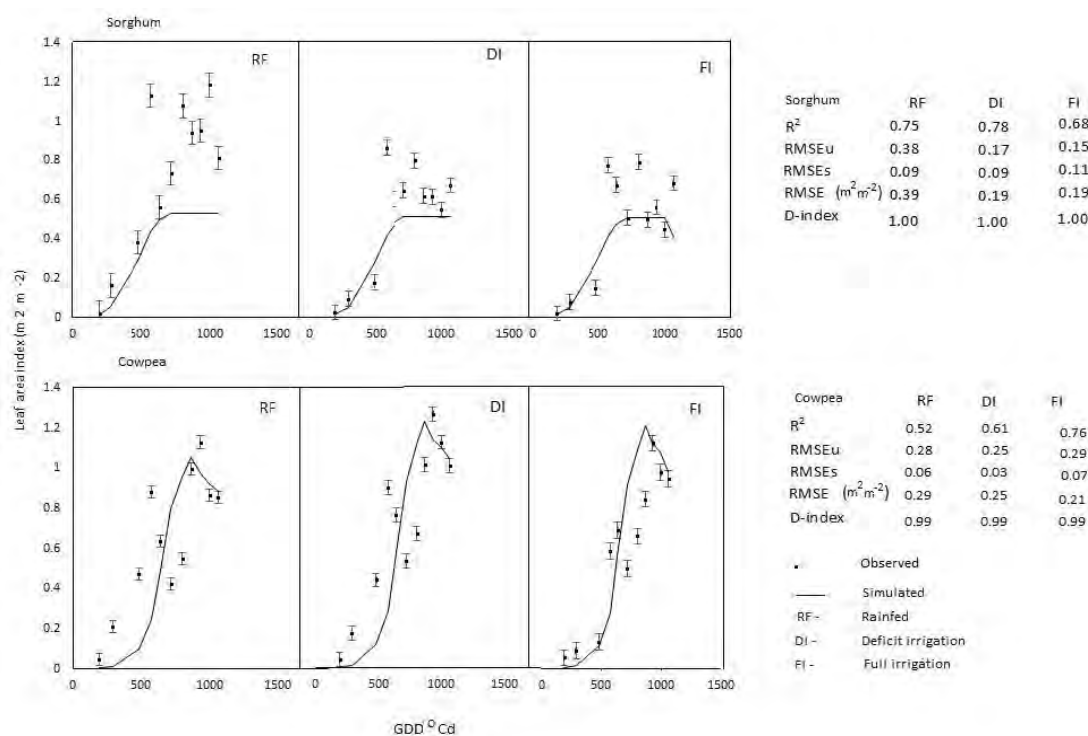
Biomass

Model simulation of biomass for sorghum gave an overall mean of 3952.15 kg ha^{-1} ± 451.08 kg ha^{-1} SD. Model simulations of biomass for sorghum under FI were very good ($R^2 = 0.95$; RMSE = 330.60 kg ha^{-1}, d – index = 1.00). The RMSEu (318.36 kg ha^{-1}) was shown to approach RMSE, although there was a 3.70% difference while RMSEs (89.14 kg ha^{-1}) was approaching zero (Fig. 8). Simulation of biomass for sorghum under DI was also very good ($R^2 = 0.96$; RMSE = 246.62 kg ha^{-1}, d – index = 1.00). The RMSEu under DI (246.42 kg ha^{-1}) was shown to approach RMSE (negligible difference of 0.008%) while RMSEs (13.70 kg ha^{-1}) was approaching zero (Fig. 8). Under RF conditions, model simulation for biomass was

173

good (R^2 = 0.96; RMSE = 494.54 kg ha^{-1}, d – index = 1.00). The RMSEu under RF (451.43 kg ha^{-1}) was shown to approach RMSE with an 8.71% difference. On the other hand RMSEs (293.24 kg ha^{-1}) was high and approaching RSME (RMSEs > 0.5 RMSE) (Fig. 8). In spite of this, model performance can be deemed as satisfactory based on R^2, RMSE and d – index. For cowpea, model simulation of biomass gave an overall mean of 2102.63 kg ha^{-1} ± 131.51 kg ha^{-1}. Model simulations for biomass under FI were satisfactory (R^2 = 0.95; RMSE = 182.36 kg ha^{-1}, d – index = 0.99). The RMSEu (167.23 kg ha^{-1}) was shown to approach RMSE, although there was an 8.29% difference while RMSEs (72.93 kg ha^{-1}) was approaching zero (Fig. 8). Simulation of biomass for cowpea under DI was also good (R^2 = 0.95; RMSE = 256.36 kg ha^{-1}, d – index = 0.99). The RMSEu under DI (225.56 kg ha^{-1}) was approaching RMSE (Fig. 8). The RMSEs (122.36 kg ha^{-1}) was high (RMSEs > 0.5 RMSE). However, model performance can still be deemed satisfactory as indicated by R^2, RMSE and d – index. Under RF conditions, model simulation for biomass was also good (R^2 = 0.92; RMSE = 336.73 kg ha^{-1}, d – index = 0.99). The RMSEu under RF (285.47 kg ha^{-1}) was shown to approach RMSE, although there was a 15.22% difference while RMSEs (168.97 kg ha^{-1}) was approaching zero (Fig. 8).

Model performance for sorghum and cowpea biomass was good and this was attributed to its conservative behaviour with RUE. These results confirmed results of local adaptation. Therefore, with regards to 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 low biomass for sorghum and cowpea were observed could be attributed to increase in root to shoot ratio. Under limited water supply, sorghum and cowpea are known to increased root to shoot ratio so as to increase root volume for enhanced 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 was able to capture response of biomass partitioning between roots and above ground in relation to water availability. Therefore, the model can be used to quantify the trade-offs of resource limitation such as reduced water availability.

Sorghum

	RF	DI	FI
R^2	0.96	0.96	0.95
RMSEu	451.43	246.24	318.36
RMSEs	293.24	13.70	89.14
RMSE (kg ha^{-1})	494.54	246.62	330.60
D-index	1.00	1.00	1.00

Cowpea

	RF	DI	FI
R^2	0.92	0.94	0.95
RMSEu	285.47	225.56	167.23
RMSEs	168.97	122.36	72.36
RMSE (kg ha^{-1})	336.73	256.36	182.36
D-index	0.98	0.99	0.99

. Observed
— Simulated
RF - Rainfed
DI - Deficit irrigation
FI - Full irrigation
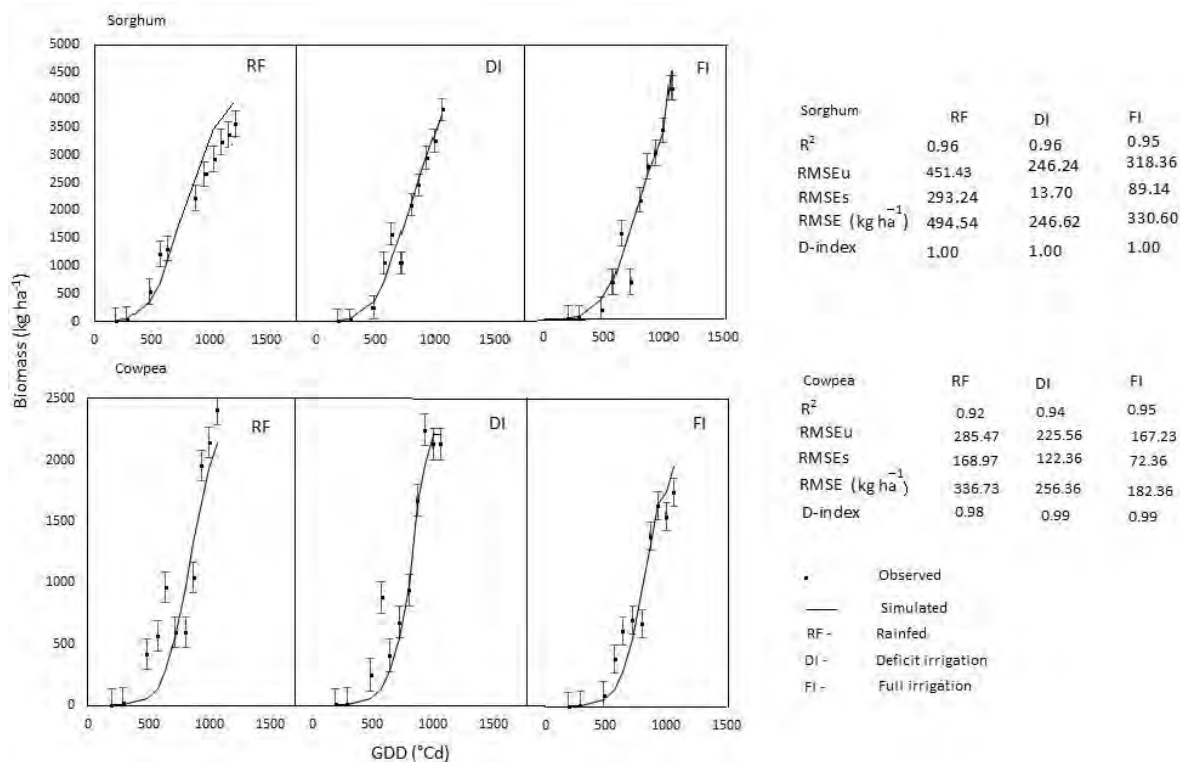
Figure 8 Comparison of observed and simulated values for sorghum and cowpea biomass (kg ha^{-1}) under different water regimes and statistical output for its evaluation. Vertical bars on observed data represent standard error (±).

Yield, water use and water use efficiency

Model simulations of yield for sorghum under DI and RF were very good (RMSE = 37.88 and 35.99 kg ha^{-1}, respectively) while simulation under FI was relatively good (145.38 kg ha^{-1}). Under DI and FI conditions, simulated yield was 3.46 and 3.34% higher while under RF conditions a larger difference of 14.93% was observed (Table 4). The large difference between simulated and observed yield for sorghum under rainfed conditions could be that the model overestimated biomass (6.5%) resulting in a successive overestimation of yield. Under field conditions, low availability of water results in a reduction in canopy size so as 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 water conditions. The use of 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. Also, 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 indices and water stress indices so as to improve sensitivity of the model to low water availability.

Model simulations of crop water use (WU) showed that it increased with increase in water availability (RF = 306.28 > DI = 361.54 > FI = 383.55 mm). Model simulations for WU for sorghum–cowpea intercrop system under FI and DI were very good (RMSE = 8.18 and 8.11 mm, respectively) while simulation under RF were relatively good (RMSE = 24.11 mm) (Table 4). Under RF and DI conditions, simulated was overestimated (7.29 and 2.29%, respectively) while under FI it was underestimated (2.08%) (Table 4). Since WU is calculated from crop transpiration and soil evaporation and due to underestimation of LA by the model larger proportion could have been utilised through soil evaporation A close look at model output showed that increase in water availability did not have an effect on crop water uptake (Ep) [FI = 113.27, DI = 112.97, RF = 111.45 mm (mean = 112.56 mm ± 0.97 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. This confirms early statement on the low sensitivity of APSIMs to water. On the other hand, increasing water availability increased soil evaporation (Es) [FI = 269.07, DI = 254.98, RF = 224.10 mm (mean = 249.38 mm ± 23 mm SD)]. Increased frequency of soil surface wetting resulted in more soil evaporation. In this regards, the model was able to proportionate further crop water use as influenced by water availability.

Results of WUEb calculated from simulated biomass and WU showed a good fit with WUEb calculated from observed biomass and WU (RMSE = 1.66, 1.97 and 3.06 kg mm^{-1} ha^{-1} for FI, DI and RF conditions, respectively) (Table 4). The calculated WUEb from model simulated biomass and WU showed that there was an underestimation of WUEb under RF conditions (14.89%) and deficit irrigation (10.75%). The model was able to simulate biomass within an acceptable range; but it overestimated WU under RF conditions and DI relative to its biomass production. However, this was considered acceptable due to observed low RMSE (3.06 and 1.97 kg mm^{-1}ha^{-1}) relative to mean values of calculated WUEb (8.75 and 8.23 kg mm^{-1}ha-1) for model simulation. The calculated WUEb from model simulated biomass and

WU showed the model under simulated (-10.99%) WUEb of the sorghum cowpea intercrop system under FI conditions; similarly this was also considered as acceptable due to the low RMSE (1.66 kg mm^{-1} ha^{-1}). Overestimation of WUEb was attributed to underestimation of WU relative to biomass produced. The sensitivity of WUE to biomass production highlights the importance of accurate its simulation as it has downstream effect on calculation of water related indices.

Table 4: Test output of APSIM model for sorghum and cowpea showing observed and simulated values for water use (mm) and yield (kg ha-1) and water use efficiency, and statistical output for its evaluation.

Water regime	Parameter	Observed	Simulated	RMSE	% Difference[1]
Rainfed	Crop water use (mm)	306.28	330.39	24.11	7.29
	Sorghum yield (kg ha^{-1})	953.63	1096.01	145.38	14.93
	WUEb (kg mm^{-1} ha^{-1})	20.60	17.54	3.06	-14.86
Deficit irrigation	Crop water use (mm)	353.43	361.54	8.11	2.29
	Sorghum yield (kg ha^{-1})	1079.23	1116.61	37.38	3.46
	WUEb (kg mm^{-1} ha^{-1})	18.41	16.43	1.97	-10.75
Full irrigation	Crop water use (mm)	391.73	383.55	8.18	-2.08
	Sorghum yield (kg ha^{-1})	1082.52	1118.51	35.99	3.34
	WUEb (kg mm^{-1} ha^{-1})	15.09	16.75	1.66	10.99

[1]% Difference is relative to observed value.

Conclusions

The APSIM model was able to 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 so as 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.

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CHAPTER 7

APPLYING APSIM FOR SORGHUM-COWPEA INTERCROP SYSTEM UNDER RAINFED PRODUCTION SCENARIOS

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Abstract

Climate change and variability has a multiplier effect on water scarcity in relation to crop production in southern Africa. With the majority of crop production being rainfed, there is need to explore strategies to improve rainfed crop productivity. Intercropping can be used to improve crop productivity through increased water use efficiency (WUE). However, limited information exists to support its adoption and subsequent management. In such instances, crop models can be used as decision support tools to complement data from field trials. The Agricultural Production Systems Simulator (APSIM) model was used to develop best management practices for improved yield and WUE for a sorghum–cowpea intercrop system for 10 years across five agro-ecologies in South Africa, namely; Richards Bay, Umbumbulu, Deepdale, Wartburg and Ukulinga. Planting dates, fertilizer rates, plant population and irrigation were considered. For Richards Bay and Deepdale ideal planting dates for high and stable yields were generated by the model. Adding fertilizer improved both yield and WUE of the intercrop by 16% in high rainfall environments. Across all environments, sorghum and cowpea plant populations of 39 000 and 13 000 plants ha^{-1}, respectively, increased yield (26.11%) and WUE (15.54%) of the intercrop system. Irrigation based on weekly rainfall events improved yield of sorghum (16.22%) and cowpea (5.36%) but reduced WUE of the system by 9.63%. Deficit irrigation was more effective resulting in yield (12.84%) and WUE (11.09%) improvements. It is concluded that APSIM can be used to develop best management practices to assist in developing guidelines for improving productivity of sorghum-cowpea intercrop systems under water scarce conditions.

Keywords: best management practices, yield, water use efficiency

Introduction

The principles of food security dictate that, in order to ensure an active and healthy life, a person must always have total access to sufficient, safe and nutritious food of their preferences to meet dietary needs (Thrupp, 2013). Rural sub-Saharan Africa (SSA) faces the challenge of achieving food security under endemic poverty, high dependence on scarce natural resources, weak institutions, poor infrastructure, and more importantly climate change and variability (Misra, 2014). Within the region, agriculture is recognised as one of many important activities for achieving food security (Cooper et al., 2008). It is small-scale and subsistence-focused; rainfed farming systems are predominant while soils are degraded (Flora, 2010). Despite moderate progress in yield improvements, crop productivity remains low and cannot provide food security for current and future demands (Dile et al., 2013; Vanlauwe et al., 2014).

Besides socio-economic and bio-physical conditions, it has been observed that climate change and variability has resulted in a shift and change in duration of growing seasons, 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 with formerly water scarce regions becoming water stressed (Schilling et al., 2012). Given this scenario, farmers may not be equipped with necessary risk management skills to adapt to the effects of climate change and variability (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 offer resilience under water scarcity and stress.

In view of the above mentioned constraints, 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 the available water – 'more crop per drop' (Molden et al., 2010). According to Fan et al. (2013), traditional cropping systems like intercropping are ideal. As it stands, research has shown that intercropping has the potential to improve overall productivity through efficient and complimentary use of water (Tsubo et al., 2003; 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 Li et al. (2011) and Chimonyo et al. (2015), this could be attributed to poor management options.

Due to limited financial resources, poor infrastructure and technical knowledge, rural farmers are generally restricted in their capacity to articulate relevant management decisions resulting in them succumbing to stress, particularly water stress (Vermeulen et al., 2012). When faced with low resource availability, Morris and Garrity (1993) pointed out that the potential of intercropping, or any other farming system, can be realised under proper agronomic management. Moreover, extension services tend to have old and standardised management plans adapted to average climatic conditions (Ripoche et al., 2011) and across variegated agro-ecologies. Thus, recommendations by extension services can be somewhat misleading, given ongoing climate change and variability, further exasperating crop loss and failure. To improve productivity and further adoption of intercropping, there is need to recalibrate current agronomic practices and also to particularise a decision support system (DSS) tool that is geared towards mitigating the risk to water scarcity and stress.

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 (Twomlow et al., 2008; Li et al., 2009; Cavatassi et al., 2011; Jat and Satyanarayana, 2013; Lehmann et al., 2013; Mbow et al., 2014). Like any business, management of farming enterprises must be guided by strategic, tactical and operational (STOP) decisions to minimise exposure to risk (Ripoche et al., 2011). Strategic management decisions often align themselves to holistic farm goals and these tend to be long term; for instance adoption of intercropping (Stone and Meinke, 2005). Tactical management options focus on implementation and determine course of action for strategic decisions (Singels et al., 2010). Emphasis is placed on farm specific information and these tend to be agronomic in nature; for instance, planting dates and fertilizer rates based on soil fertility results. Operational management options are decisions made on a day to day basis and are often in response to or impeding risk (Singels et al., 2010). For example, irrigation and weeding are management decisions often taken on a day to day basis. 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 information with respect to the type of management decisions to be

189

made. Therefore, farmers need an efficient, relevant and accurate way to evaluate data for specific management decisions. To improve farmers' capacity to make 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 (Holzworth et al., 2014).

Crop simulation models are computerised mathematical representations of crop growth, development and production, all as a function of weather and soil conditions, and management practises that can reliably determine "what if" and "when" scenarios across diverse cropping system. Crop simulation models like APSIM 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 locally adapted model of APSIM for a sorghum–cowpea intercrop to assess different management scenarios for several rainfed agro-ecologies in KwaZulu–Natal climatic conditions for best management practices. Secondary to this, to use the model to identify best management practises for improve water use efficiency for sorghum–cowpea intercrop systems that are better adapted to subsistence smallholder sorghum farming in the region. The latter is achieved through scenario analyses based on long term (10 years) simulations. Planting dates, fertilizer rates, plant population and irrigation were factors considered for the scenario analyses.

Material and methods

Description of Selected Environment

KwaZulu–Natal has a diverse agro-ecology with 590 bio–resource units (BRUs) (Camp, 1999). It has a warm, sub-tropical, maritime climate, with temperatures moderated by the expanse of the Indian Ocean. Summers are hot and humid, averaging 28°C and experience the majority of the annual rainfall, while winters, with average temperatures of 23°C, are warm and dry with occasional frost in the interior. Generally, the coast is subtropical with inland regions becoming progressively colder. To the south (along the coat) the annual rainfall average is 1009 mm, with daytime maxima of 28°C from January to March. Temperature drops towards the inland regions, with similar summer maxima, but much

cooler in the winter (15°C). The northern regions are very warm 30 – 32°C in the summer, but may drop below freezing point on winter evenings.

Five sites located in different BRUs in KwaZulu–Natal (Deepdale, Richards Bay, Umbumbulu, Ukulinga and Wartburg) (Table 1) were used for model scenario analyses. Climate data for each site was sourced from the SASRI weather portal (http://sasex.sasa.org.za/irricane/tables/Ash_tables_AR.pl) using the nearest station to the location with the exception of Ukulinga where there is a weather station on site. Richards Bay was considered as a low potential environment even though there is considerably high annual rainfall (Table 1). The location is characterised by sandy soils which are generally considered as having low agricultural potential. Sandy soils, because of the particle size and large pore spaces between the particles do not hold nutrients and water. Ukulinga and Deepdale were considered as moderate potential environments based on the annual rainfall received (Table 1). Umbumbulu and Wartburg were considered as high potential environments since they received high annual rainfall and have clayey soils. In contrast to sandy soils, clayey soil retain more water and nutrients (Table 1).

A three-step procedure was used for scenario analyses of sorghum –cowpea intercrop. These were:-

i.   Model parameterisation and validation for the growth of sorghum-cowpea intercrop under local conditions;

ii. Sensitivity analyses to determine the variables requiring most careful definition and;

iii. Scenario analyses which involved the assessment of model output when using climate and soil data run from selected environments under variable management options.

Local adaptation and model testing

Local adaptation and testing of the APSIM sorghum–cowpea model were done using data obtained from two year field experiments of a sorghum–cowpea intercrop established at the University of KwaZulu–Natal's Ukulinga Research Farm. For details of field experimental output and model performance, refer to Chimonyo et al. (in review).

Sensitivity Analyses

Prior to running the scenario analyses, sensitivity analyses was conducted to determine parameters which had a pronounced effect on model output. The sensitivity analysis involved changing one parameter at a time to values of ±10% for default input parameters and running the model. The percentage change in simulated yields, over the range of values of the parameter, was compared with the variability of observed yield using relative sensitivity. Relative sensitivity is the relative change of the variable in relation to a change in the parameter. The index is dimensionless and gives a good point for comparing multi-factors.

$$\text{Relative sensitivity} = \frac{\Delta Y_i(X_j)}{\Delta X_i} \cdot \frac{1}{Y_i}$$ **Equation 13**

where the relative sensitivity shows the relative change, $\Delta Y_{i/}$ Y_i of variable Y_i in relation to change of ΔX_i of parameter X_j.

Sensitivity analysis is an analytical tool used to quantify magnitude of influence for parameters on predicted output (Wang et al., 2013). Results of sensitivity analysis showed that the most sensitive parameters were management level parameters and these were planting dates, amount of fertilizer applied, soil pH and initial soil water content (results not shown). Developers of CSMs have recognised the important effect of crop management in managing environmental risks. It could be that these parameters have been made sensitive so as to provide a broad response to large and variable agro-ecological zones. Sensitivity analyses confirmed the need for continual research into best management practises for improved productivity. It also formed the basis of scenario analyses were planting dates, fertilizer application rates, plant population combinations and irrigation were then considered.

Simulation

Simulations were performed using APSIM version 7.7. Details of model simulations are described below.

Climate

For each agro-ecology, 10 year (2004 – 2014) weather data that contained daily estimates of rainfall, minimum and maximum temperatures, solar radiation and reference evapotranspiration was sourced from SASRI weather site (http://sasex.sasa.org.za/irricane/tables/Ash_tables_AR.pl) using the nearest station to the location except for Ukulinga where there was a weather station on site (Table 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".

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-ecology, 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). The soil file selected in APSIM to best represent this description was Clay_Shallow_MF_101mm (Table 2). Soils from Richards Bay were described as relatively deep and sandy with low fertility (Motsa et al., 2015). The soil file selected in APSIM to best represent soils in Richards Bay was Sandy_Medium_LF_111mm (Table 3). Soils in Umbumbulu and Deepdale were similar and were described as relatively deep and clayey with medium fertility (Motsa, 2015; Table 4). The soil file selected to best represent these environments was Clay_Medium_MF_171mm. Soils in Wartburg were described as relatively deep and clay loam - loamy with medium (Chibarabada, 2015; Table 5). The soil file selected in APSIM to best represent was Loam_Medium_MF_125mm.

193

Table 1: Climate and soil description of sites to be included in the simulation.

	*Deepdale	*Richards Bay	Umbumbulu	**Ukulinga	**Wartburg
Geographical location	28º01'S; 28º99'E	28°19'S; 32°06E	29º98'S; 30º70'E	29º37'S; 30º16'E	29.42° S, 30.57° E
Altitude (m a.s.l.)^z	998	30	632	775	880
Bio-resource group/ agro-ecological zone	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; K5/2274//4 Del No.4).

Table 2: Properties of the African (generic) soil series available in APSIM's soil module with best describes soil water properties in Ukulinga (the effective root zone for crops was considered to be 0-60 cm).

Depth (cm)	Bulk density (g cm^{-3})	Air Dry[1]	LL15[2]	DUL[3]	SAT[4]
		—————————(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

1Air Dry – Hygroscopic soil water content.
2Crop lower limit (LL15) – Permanent wilting point (PWP) lower limit of the available soil water range and is a point when plants have removed all of the available water from a given soil, they wilt and will not recover.
3Drained upper limit (DUL) - Field capacity (FC) amount of water remaining in a soil after the soil has been saturated and allowed to drain for approximately 24 hours.
4Saturation (SAT) - Saturation is when all pores in a soil are filled with water.

Table 3: Properties of the African (generic) soil series available in APSIM's soil module with best describes soil water properties in Richards Bay (the effective root zone for crops was considered to be 0–120 cm).

Depth (cm)	Bulk density (g cm^{-3})	Air Dry[1]	LL15[2]	DUL[3]	SAT[4]
		—————————(mm 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

1Air Dry – Hygroscopic soil water content.
2Crop lower limit (LL15) – Permanent wilting point (PWP) lower limit of the available soil water range and is a point when plants have removed all of the available water from a given soil, they wilt and will not recover.
3Drained upper limit (DUL) - Field capacity (FC) amount of water remaining in a soil after the soil has been saturated and allowed to drain for approximately 24 hours.
4Saturation (SAT) - Saturation is when all pores in a soil are filled with water.

Table 4: Properties of the African (generic) soil series available in APSIM's soil module with best describes soil water properties in Umbumbulu and Deepdale (the effective root zone for crops was considered to be 0–120 cm).

Depth (cm)	Bulk density (g cm⁻³)	Air Dry	LL15	DUL	SAT
			$(mm\ mm^{-1})$		
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
60–90	1.200	0.290	0.290	0.420	0.470
90–120	1.200	0.320	0.320	0.425	0.475

1Air Dry – Hygroscopic soil water content.
2Crop lower limit (LL15) – Permanent wilting point (PWP) lower limit of the available soil water range and is a point when plants have removed all of the available water from a given soil, they wilt and will not recover.
3Drained upper limit (DUL) - Field capacity (FC) amount of water remaining in a soil after the soil has been saturated and allowed to drain for approximately 24 hours.
4Saturation (SAT) - Saturation is when all pores in a soil are filled with water.

Table 5: Properties of the African (generic) soil series available in APSIM's soil module with best describes soil water properties in Wartburg (the effective root zone for crops was considered to be 0-120 cm).

Depth (cm)	Bulk density (g cm⁻³)	Air Dry	LL15	DUL	SAT
			$(mm\ mm^{-1})$		
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

1Air Dry – Hygroscopic soil water content.
2Crop lower limit (LL15) – Permanent wilting point (PWP) lower limit of the available soil water range and is a point when plants have removed all of the available water from a given soil, they wilt and will not recover.
3Drained upper limit (DUL) - Field capacity (FC) amount of water remaining in a soil after the soil has been saturated and allowed to drain for approximately 24 hours.
4Saturation (SAT) - Saturation is when all pores in a soil are filled with water.

Scenario analyses

Four management options were used to develop scenarios used as a guide to develop recommendations for best management practises. The scenarios were:-

Scenario 1: Planting dates

Three approaches were used to establish planting dates and these were, trigger season climate method, modelling and fixed date approach. 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 (White et al., 2001). For this method, the onset of the season is assumed to be when the ratio of sum total of monthly rainfall and reference evapotranspiration (ET_o) becomes greater than 0.5.

$$\frac{Rainfall}{Reference\ Evapotranspiration} \geq 0.5$$ **Equation 14**

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 were rainfall exceeds 0.5 ET_o.

Rainfall $\geq$ 0.5 Reference Evapotranspiration **Equation 15**

An advantage to this approach is that it is site specific if weather data is available. On the other hand, a major limitation towards practical application of this method would be that farmers and extension service providers may 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's Bay, trigger season occurred on the 1st of October while it occurred on the 1st and 15th of September for Umbumbulu and Wartburg, respectively (Fig. 1).
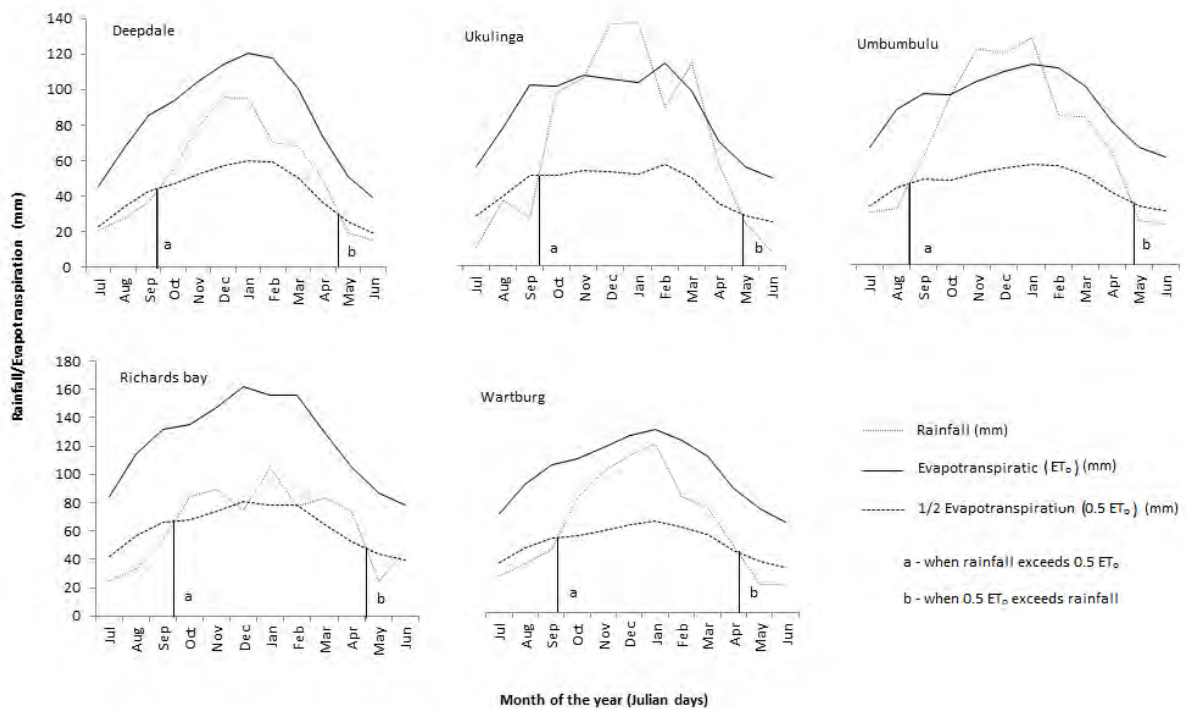
Figure 1: Determination of start and end of growing season for Deepdale, Richards Bay, Umbumbulu, Ukulinga and Wartburg using monthly average data over 10 years for rainfall, reference evapotranspiration (ET_o) and 0.5 ET_o. The onset of a growing season (*a*) is when rainfall exceeds 0.5 ET_o. The period 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.

The current planting dates in use by most subsistence 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 SSA (Muzari et al., 2012). For instance, sorghum production guidelines published in 2010 by the Department of Agriculture, Forestry and Fisheries: Agricultural Research Commission suggest that sorghum should be planted between the 1st of October and mid-December throughout South Africa. As it is, South Africa exhibits a wide variation of agro-ecologies, both at micro and macro level. Due to climate change and variability this variation has increased and there is an observed increase in land area occupied by semi-arid

and arid agro–ecologies 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. However, a major weakness of this approach is the need to redefine the dates because of continuously shifting agro-ecological zone boundaries. Five planting dates covering a period from 15 September to 15 January were then used for the simulation. Corresponding planting dates were 15th of September, October, November, December and January, respectively; these dates were thought to be representative of early to late planting.

As a management tool, most crop simulation models are able to generate planting dates from climate and soil data. This is done based on a predefined criteria that takes into account amount of rainfall and 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 for a trained personal. They are also site-specific thus improving the accuracy of recommendations. However, one of the drawbacks to CSMs is that without the necessary technical skills and parameter inputs information generated may be misleading. For each site, APSIM was used to generate planting dates using a user defined criteria 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 yield and WUE, planting dates with the highest frequency of appearance within the 10 year weather data set was used for scenario analysis (Table 6).

Table 6: Model generated planting dates for the agro-ecological zones (Wartburg, Deepdale, Richard 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 model.

Scenario 2: Fertilizer application rates and time of application

Sorghum requires about 85 kg N ha^{-1} to achieve a tonnage of 2 – 3.5 tonnes per hectare (Wylie, 2004). Grain sorghum yields in SSA average ≈ 900 kg ha^{-1} as 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.

Scenario 3: Plant populations

To determine optimum plant population for the component crops for each site, simulations were done using plant populations that were 50% less and 50% more of 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, with a crawling growth habit, optimum plant populations of 13 000 plants ha^{-1} were used. These have been observed to give the best productivity in terms of land equivalent ratio of intercrop systems (Oseni, 2010). The populations used in the analyses assumed that populations less than the recommended will reduce resource competition and improve productivity for either component crop. It was also

assumed that higher populations would improve resource utilisation of the system. Simulations were carried out by maintaining the recommended plant population of one component and changing the other resulting in a number of 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}; and

- the baseline population (C1) used to compare changes in yield and WUE was sorghum and cowpea plant population of 26 000 and 13 000 respectively.

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 plant available water (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. Rainfall is often unevenly distributed resulting in intermittent water stress and hence causing considerable yield losses (Nouri-Ganbalani et al., 2009). It is assumed that the introduction of irrigation in areas under physical water scarcity can significantly increase agricultural 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

201

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.

Data analyses and evaluation

Within the model, WU was determined as the sum of crop water uptake (Ep) from the whole profile (sorghum Ep + cowpea Ep) and soil evaporation (Es). Each scenario was run independent from each 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:

$$WUEy = \frac{Y}{WU} (kg\ mm^{-1}\ ha^{-1})$$ **Equation 3**

where: WUE = water use efficiency (kg mm^{-1} ha^{-1}), Y = total grain yield (sorghum + cowpea) (kg ha^{-1}), (kg 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.

Results and discussion

Rainfall

Rainfall varied across all sites and across months within each year (Table 7). In general, high mean rainfall was observed at Umbumbulu (900.1 mm) while low rainfall was observed in Deepdale with 647.63 mm per year (Table 7). On average, high (822.06 mm) but variable rainfall was observed at Ukulinga (± SD19.60 – 98.71) while least variation was observed at Deepdale (± SD 11.18 – 37.82). The observed variations for Ukulinga rainfall would suggest that the risk of water related crop failures was high (Table 7). On the other hand, rainfall

received at Deepdale was stable but low, suggesting that if an ideal cropping system was adopted, the risk to crop failure would be low and stable yields could be observed.

Table 7: Comparison of mean rainfall and its variability across different environments (Richards Bay, Umbumbulu, Deepdale, Wartburg and Ukulinga).

Month	Richards Bay	Umbumbulu	Deepdale	Wartburg	Ukulinga
Jan	$102.99^{\pm93.48*}$	$132.50^{\pm54.22}$	$98.35^{\pm35.73}$	$105.00^{\pm35.89}$	$133.46^{\pm98.71}$
Feb	$82.65^{\pm55.51}$	$76.32^{\pm46.40}$	$70.41^{\pm31.86}$	$77.43^{\pm57.91}$	$87.00^{\pm55.19}$
Mar	$83.77^{\pm46.04}$	$91.67^{\pm44.11}$	$72.08^{\pm28.28}$	$83.86^{\pm34.98}$	$111.36^{\pm46.06}$
Apr	$73.79^{\pm48.28}$	$62.35^{\pm36.23}$	$50.52^{\pm31.25}$	$73.85^{\pm36.23}$	$56.26^{\pm48.28}$
May	$24.87^{\pm18.70}$	$21.07^{\pm19.28}$	$17.03^{\pm19.80}$	$24.94^{\pm18.82}$	$23.16^{\pm19.60}$
Jun	$50.95^{\pm70.01}$	$22.49^{\pm22.41}$	$13.70^{\pm11.18}$	$46.76^{\pm67.89}$	$7.43^{\pm61.76}$
Jul	$26.87^{\pm33.27}$	$29.83^{\pm61.76}$	$14.49^{\pm24.90}$	$24.62^{\pm33.77}$	$13.46^{\pm35.10}$
Aug	$36.15^{\pm59.34}$	$35.38^{\pm35.10}$	$24.77^{\pm25.03}$	$33.17^{\pm59.34}$	$10.00^{\pm50.54}$
Sep	$57.64^{\pm43.64}$	$66.41^{\pm50.54}$	$37.65^{\pm37.37}$	$52.87^{\pm43.64}$	$35.63^{\pm38.48}$
Oct	$91.56^{\pm41.37}$	$108.67^{\pm38.48}$	$64.39^{\pm22.07}$	$83.96^{\pm41.37}$	$25.76^{\pm45.91}$
Nov	$98.00^{\pm43.50}$	$133.59^{\pm43.55}$	$84.70^{\pm29.32}$	$89.87^{\pm42.87}$	$95.27^{\pm43.55}$
Dec	$81.57^{\pm33.70}$	$119.85^{\pm47.54}$	$99.54^{\pm37.82}$	$74.83^{\pm7.98}$	$103.27^{\pm67.87}$
Mean monthly	67.56	75.01	53.96	64.26	68.55
Mean yearly total	810.81	900.13	647.63	771.16	822.06

*Mean yield for 10 year simulation and SD – Standard deviations within the 10 year simulation showing rainfall variability.

Scenario 1: Planting Dates

Different scenarios for planting date 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 (± SD 185.42), 987.5 (± SD 149.37), 820.5 (± SD 122.99), 879.6 (± SD 231.97) and 935.8 kg ha^{-1} (± SD 122.19), respectively. Yield averages for cowpea were 281.0 (± SD 86.39), 355.9 (± SD 153.24), 139.6 (± SD 55.69), 260.1 (± SD 153.36) and 321.7 kg ha^{-1} (± SD 110.58), respectively. The observed yields for

sorghum and cowpea were attributed to rainfall observed for each environment. Low yields observed for Deepdale for both sorghum and cowpeas could be due to the overall low rainfall at this site (see Table 7) while high yields observed for Umbumbulu, Richards Bay and Ukulinga were attributed to high rainfall received at the 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 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 yield of cowpea within the intercrop system are influenced by population density.

The ideal planting date is a scenario where overall yields 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-Novermber) and this yielded an average of 1050.65 kg ha^{-1} (±SD 45.57) for sorghum and 355.57 kg ha^{-1} (± SD 50.57) for cowpea. Similarly, the model generated planting date for Deepdale (21 November) simulated high yields for both sorghum [959.79 kg ha^{-1} (± SD 88.81)] and cowpea [160.57 kg ha^{-1} (+/- SD 38.57)] (Fig. 2). For Umbumbulu, Wartburg and Ukulinga, ideal planting dates that gave high and stable yields for sorghum [970.83 kg ha^{-1} (± SD 106.32), 1037.24 kg ha^{-1} (± SD 68.78), 995.87 kg ha^{-1} (± SD 88.81), respectively] were observed by using a fixed planting date (15-October, 15-October and 15-Novermber, respectively). The fixed planting dates did not always give high yields for cowpea, but results show yield stability as observed by low standard deviation relative to other planting dates [426.22 kg ha^{-1} (± SD 134.94), 332.78 kg ha^{-1} (±SD 115.08), 347.43 kg ha^{-1} (± SD 97.76), respectively].

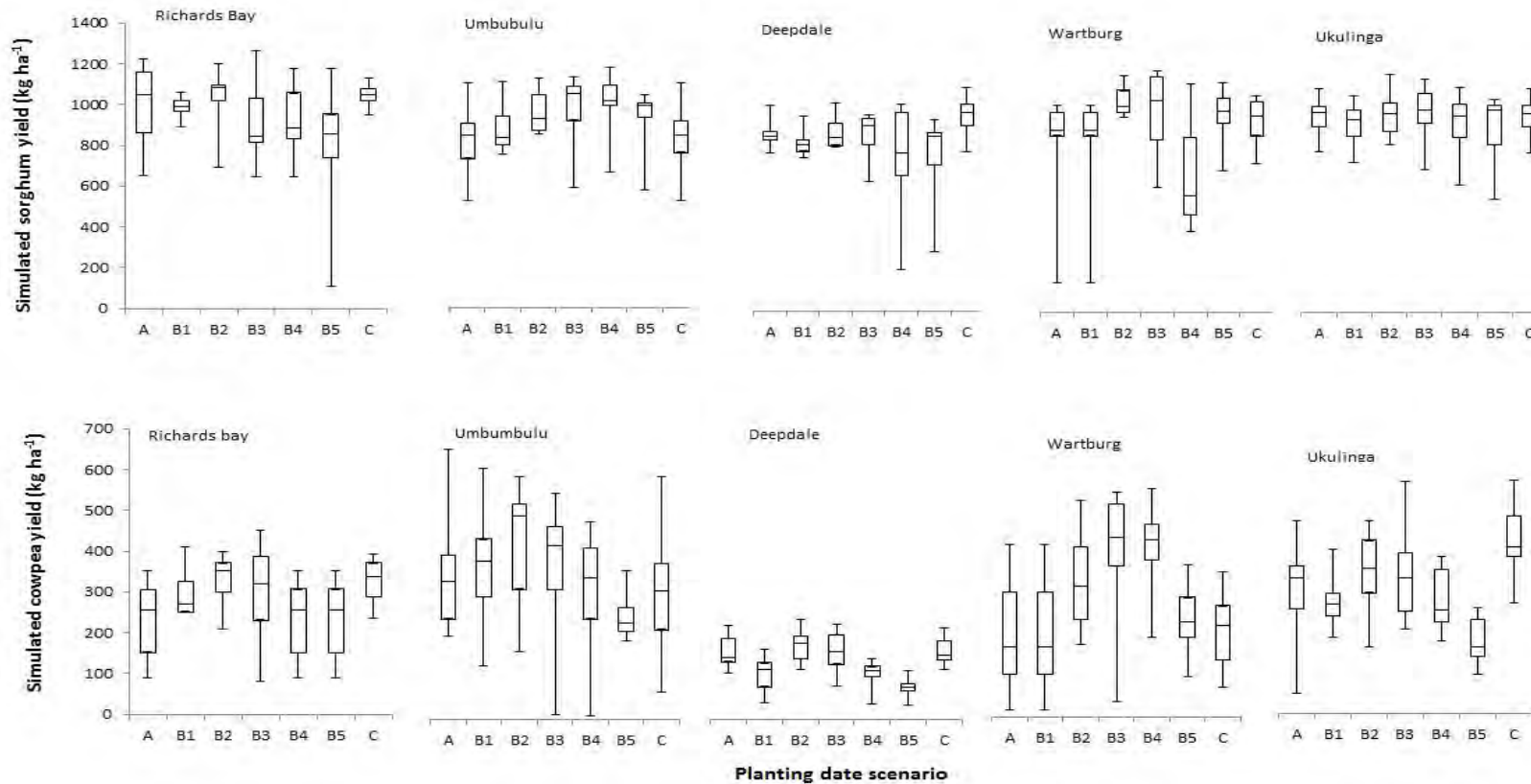Figure 2: Simulated yield response of sorghum-cowpea intercrop system across the five environments (Richards Bay, Umbumbulu, Deepdale, Wartburg and Ukulinga) for different planting date scenarios (A- site specific planting date defined by trigger season method; B – fixed planting dates starting from B1 – 15 Sept, B2 – 15 Oct, B3 – 15 Nov, B4 – 15 Dec, B5 – Jan; C – planting dates generated by APSIM.

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 interval so as to maintain desired 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 to for an ideal planting conditions. Fixed planting dates for Umbumbulu, Ukulinga and Wartburg were within the official planting window (15 Oct − 15 Dec) for sorghum within the KwaZulu Natal region (Directorate Plant Production/Agriculture Research Council, 2010). During this period rainfall amount was observed to be high and stable. SWC is sufficient for seed germination and thereafter to sustain growth of developing seeding.

In low rainfall areas (Deepdale and Wartburg), 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 at high rainfall environments was associated with low water use while yield remained unchanged (Table 8). 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. Where seed and fertiliser are more readily available, double cropping with early maturing cultivars of sorghum and cowpea can be employed to increase temporal use of water. In the context of sorghum-cowpea intercrop system, double cropping would be growing the cropping system twice in the same season in a relay manner.

Table 8: Comparison of simulated sorghum and cowpea yield, water losses, total water used and water use efficiency in response to different environments and planting dates.

Environment	Planting date	Sorghum yield	Cowpea yield	[1]Rainfall	[2]Water lost	[3]Cowpea water uptake	[4]Sorghum water uptake	[5]WU	[6]WUE	[7]WUE impr.
		——kg ha^{-1}——		————————————————mm————————————					kg ha^{-1} mm^{-1}	%
R. Bay[8]	15 Jan	983.64	296.37	278.22	232.66	31.97	27.15	291.79	4.42	15.15
Umbumbulu	16 Jan	951.15	251.71	314.14	286.26	33.98	21.68	343.11	3.56	10.82
Deepdale	15 Sep	811.52	104.01	246.57	199.47	23.15	32.08	254.71	3.86	8.29
Wartburg	15 Sep	928.23	249.92	259.91	229.15	38.44	25.03	322.62	3.91	14.52
Ukulinga	15 Jan	904.73	196.02	309.17	276.57	29.84	23.58	330.00	3.51	19.11

[1]Ten 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).
[8]Richards Bay.

Scenario 2: Fertilizer Application Rate

Long term simulation showed that overall yields were improved with the use of fertilizer (Table 9). The observed results were attributed more to an increase in sorghum yields than cowpea. Overall, adding 85 kg N ha^{-1} had a more positive effect (12.7%) on sorghum yield than when 42.5 kg N ha^{-1} was applied (5.7%). Results of simulations show that sorghum yields at Wartburg, Umbumbulu and Ukulinga were more responsive to fertilizer application (Table 9) 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 due to the fact that plants absorb less nitrogen when soil water content is low (Gaydon et al., 2011). 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 of sorghum yield in Richards Bay could also be attributed to leaching during rainfall events.

Richards Bay is characterised by sandy soils which are generally associated with leaching (Drechsel et al., 2015). 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. Then again, the returns on fertiliser application in sites like Ukulinga and Deepdale can still be increased by increasing fertiliser rates up to an optimum rate where monetary value of yield obtained is high that the cost of fertiliser used to obtain it.

Overall, adding fertilizer improved WUE for the different environments. Overall, adding 85 kg N ha^{-1} had a more positive (5.08%) effect on WUE for the intercrop system than when 42.5 kg N ha^{-1} was applied (3.43%). Overall improvements of 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 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 Li et al. (2015) and Gan et al. (2010) who observed an improvement of 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 9: Yield simulations of sorghum in sorghum-cowpea intercrop system, yield and water use efficiency improvements of the system for the different environments in response to fertilizer and.

Fertilizer	Environment	Sorghum	Cowpea	Water use	WUE[1]	ΔYield[2]	ΔWUE[3]
		——kg ha^{-1}——		mm	kg ha^{-1} mm^{-1}	——%——	
0 kg N ha^{-1}	Umbumbulu	951.15	251.71	286.26	4.87	-	-
	Ukulinga	904.73	196.02	363.11	3.12	-	-
	Richards Bay	913.64	226.37	258.66	4.45	-	-
	Deepdale	811.52	104.01	282.63	3.24	-	-
	Wartburg	928.23	249.92	308.93	3.82	-	-
42.5 kg N ha^{-1}	Umbumbulu	1002.36	296.98	301.79	4.64	5.12	5.14
	Ukulinga	915.43	197.51	363.11	3.06	4.56	0.62
	Richards Bay	952.53	232.62	259.71	4.63	5.13	4.92
	Deepdale	923.53	104.36	312.86	3.28	2.97	2.33
	Wartburg	1023.91	249.42	331.90	3.96	7.91	3.73
85 kg N ha^{-1}	Umbumbulu	1060.36	295.34	306.79	4.69	12.51	6.97
	Ukulinga	988.79	196.82	360.11	3.29	15.65	2.74
	Richards Bay	1006.72	295.48	253.71	4.71	7.63	3.52
	Deepdale	992.46	103.28	312.86	3.50	3.23	4.26
	Wartburg	1126.82	238.96	321.76	4.24	23.12	7.91

1Water use efficiency
2ΔYield –Change in yield
3Water use efficiency changes relative to calculated WUE simulated from simulated crop water use [crop water uptake unproductive, water loss (soil evaporation, drainage and runoff)] under 0 kg N ha^{-1}.

### *Scenario 3: Plant populations*

Results of plant populations 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 kg ha^{-1} (± SD 125.36)]. It could be that cowpea did not compete with sorghum for resources such as radiation and

water. It would suggest that plant population of cowpea can still be increased further. Contrary to this, cowpea yield was affected by the change in sorghum population (Fig. 3). Throughout all the environments, reducing sorghum plant population improved cowpea yield by between 5.6 – 35.1% (results not shown). Although, increasing sorghum population increased its overall yield, results showed that this had a negative effect (12.63 – 16.38 % reduction) on simulated cowpea yield (Table 10). It could be that sorghum was a stronger competitor for resources (radiation and water) than cowpea. Reducing or increasing plant population of one component crop has been shown to affect the availability of resources to another component crop in an intercrop system (Gharineh and Moosavi, 2010). Increasing sorghum population might have increased the extinction coefficient of the top layer canopy and reduced the amount of solar radiation received by cowpea, the understory. To improve yield of cowpea under high sorghum population, changing row orientations and arrangements can reduce competition for resources between sorghum and cowpea. Currently nutrition within the SSA context is poor because diets are mostly starch based and area under cereal cultivation is high relative to legumes. Increasing legume populations within intercrop systems will not affect cereal output but will improve availability of protein rich food alternatives for marginalized communities.

Under 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 was somewhat unchanged for each environment relative to the baseline (results not shown). 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.
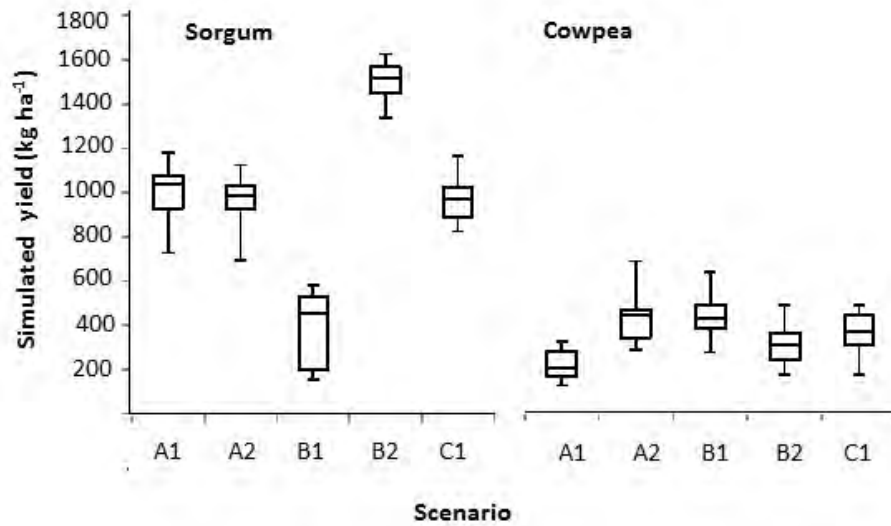
Figure 3: Simulated mean yield response of sorghum-cowpea intercrop system across the five environments (Richards Bay, Umbumbulu, Deepdale, Wartburg and Ukulinga) in response to different plant populations (A1 – Sorghum 26 000 plants ha^{-1} and cowpea 6 500 plants ha^{-1}; A2 - Sorghum 26 000 plants 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 10: Comparison of simulated sorghum and cowpea yield, water losses, total water used and water use efficiency in response to different environments and plant population.

Environ.	Cowpea yield	Sorghum yield	Average rainfall	[1]Water lost	[2]Cowpea water uptake	[3]Sorghum water uptake	[5]WU	[6]WUE kg ha⁻¹ mm⁻¹	[7]ΔWUE[4] %
	——kg ha⁻¹——		————————mm————————						
R. Bay[8]	228.10	1271.04	302.00	260.40	39.96	39.96	340.32	4.79	7.84
Umbumbulu	318.36	1390.88	456.97	391.02	45.89	33.55	470.47	3.75	3.10
Deepdale	144.46	1203.22	284.14	225.88	34.52	49.49	309.89	4.45	13.29
Wartburg	375.28	1323.18	569.95	475.31	64.83	39.01	579.15	3.41	4.68
Ukulinga	1453.75	360.27	421.03	322.92	37.83	37.83	404.78	4.61	23.81

[1]Ten 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 changes observed WUE relative to WUE obtained from baseline plant populations of 26 000 and 13 000 plants ha⁻¹ for sorghum and cowpea, respectively.
[8]Richards Bay.

Scenario 4: Irrigation

Irrigation improved productivity and WUE of the sorghum–cowpea intercrop system (Table 11). Irrigating at weekly intervals based on rainfall analysis (WIR) simulated higher yields (5.63%) relative to irrigation scheduling based on allowable soil water depletion (ASWD) across all the environments (Table 11). This could be because irrigating based on weekly rainfall events increased availability of water and the crop was not exposed 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 also good aeration and drainage. In contrast, soils at Richards Bay are deep and sandy and these soils are inherently well–drained, 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. Contrary to this, results of simulation 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). Scheduling irrigation based on weekly rainfall events can result in wasteful use of water by over application of water relative to crop water requirements (Jumman, 2008). This was quite evident with high amounts of water lost were through unproductive means (Table 11).

Overall irrigation reduced WUE of the intercrop system relative to under 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 were, 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 regards, 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: 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[4]	WU[5]	WUE[6] kg ha^{-1} mm^{-1}
		——kg ha^{-1}——		——————————————————mm——————————————————							
Deficit irrigation	Umbumbulu	296.34	926.52	298.90	276.16	48.24	25.70	33.60	332.50	383.70	3.18
	Ukulinga	384.04	996.56	456.97	392.79	54.32	23.79	7.27	464.25	478.17	2.88
	R. Bay[7]	429.71	1209.31	284.14	244.09	35.39	49.85	36.36	320.50	365.69	4.48
	Deepdale	142.85	896.67	567.34	499.90	74.78	26.35	26.04	593.37	627.07	1.65
	Wartburg	406.88	999.99	360.10	330.39	68.34	26.18	50.00	410.10	474.91	2.96
Rainfall	Umbumbulu	315.75	972.81	298.90	332.97	51.35	26.31	109.09	407.99	519.72	2.48
	Ukulinga	384.33	996.72	456.97	428.84	54.40	23.72	45.45	502.43	552.41	2.50
	R. Bay	429.33	1346.69	284.14	316.30	33.94	53.61	95.45	379.59	499.31	3.55
	Deepdale	143.65	935.56	567.34	673.60	74.72	27.09	200.97	768.31	976.38	1.10
	Wartburg	395.92	1009.27	360.10	371.23	64.94	26.39	64.00	424.10	526.56	2.66

[1]Ten 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.

Recommendations for best management practices

Based on model scenario analyses, the following recommendations could be made for sorghum–cowpea intercrop system.

a) To achieve high and sustainable yields, environments that receive low potential areas similar to Deepdale and Wartburg (low annual rainfall) and Richards Bay (deep sandy soils) should plant intercrop of sorghum-cowpea around the 15th of November.

b) Environments that receive high rainfall and are characterised by shallow clay soils like Ukulinga need to plant sorghum–cowpea intercrop system around the 15th of December. On the other hand, in high rainfall areas with deep clay soils similar to Umbumbulu and Wartburg, planting should be done on the 15th of October

c) To achieve high WUE, early planting (15 September) in low rainfall areas is most desirable while in high rainfall areas, late planting (15 January) is recommended.

d) Farmers in environment similar to Deepdale are recommended to add 42.5 kg N ha^{-1} since adding high quantities fertilizer will not always improve yield and WUE.

e) Fertilizer levels of 85 kg N ha^{-1} is recommended for use in high rainfall environments such as Ukulinga, Richards Bay and Wartburg since it was evident that it improved both yield and WUE.

f) 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 ha^{-1} in combination with 13 000 plants ha^{-1} of cowpea.

g) When yields of both crop species are desired aincreasing cowpea plant population to 19 500 plants ha^{-1} while sorghum can be maintained at 26 000 is recommended. There is still need to research into alternative combinations of plant populations still needs to be research so as give environment specific recommendations.

h) For all the environments, weekly scheduling of irrigation based on weekly rainfall amount resulted in high yields; however this also produced low levels of WUE. It can be recommended that, for all environments, using soil water deficit is more ideal since yield and WUE did show some improvements relative to weekly scheduling of irrigation based on weekly rainfall amount.

Conclusions

The model 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 was able to identify best management practices for improved water use efficiency for sorghum–cowpea intercrop under rainfed conditions. For environments included in this study, 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 analysis. There is still need to apply APSIM to assess the effects of the combinations of these management options on yield and WUE for sorghum–cowpea intercrop system.

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CHAPTER 8

GENERAL DISCUSSION, CONCLUSION AND RECOMMENDATIONS

Introduction

Global population is expected to reach 9 billion by 2050 (Bremner et al., 2010). This will be coupled with an increase in the demand for food (Ye et al., 2013). In addition, improving incomes also mean that people are now able to demand more food. Food production will have to increase to meet the increased demand (Rosegrant et al., 2014). Within sub-Saharan Africa, food production is primarily governed by water resources (Rosegrant et al., 2014). Agriculture remains the major user of water, although there are limits to this since pressure from competing users is increasing (Ye et al., 2013). Water for agriculture has further been constrained due to the increased occurrence and severity of drought resulting from climate change and variability (Bollig and Feller, 2014). To increase resilience to current and future water uncertainties, integrated approaches that allow improved water productivity and sustainability are required (De Schutter, 2012). Sorghum is drought tolerant and has long since been considered as an ideal crop under water scarce environments (Blum, 2009; Cavatassi et al., 2011). Including sorghum in intercrop systems could increase resilience against observed and predicted water scarcity. In this study, it was hypothesised that intercropping sorghum with either cowpea or bottle gourd improves resource use and resilience. To test this hypothesis, field and modeling approaches were used to determine the productivity and resource use efficiency of a sorghum–cowpea–bottle gourd intercrop system under different water regimes.

General discussion

Resource use in intercrop systems

A review of literature was initially undertaken (Chapter 2). The objective of the review was to elaborate on concepts in intercropping and outline how resources are captured and utilised within the system. It was observed that the key to success in intercropping was complimentary or non–competitive use of resources, over a spatial and temporal scale. This could be achieved when intercropped plants captured resources at different depths within the soil profile. In addition, through relay cropping, crop growth cycle at a locality could be extended beyond that of a monocrop system thus extending resource capture. The review also showed that aboveground interactions within intercrop systems have thoroughly been investigated while belowground interactions were mostly limited to extrapolations from biomass partitioning. This posed as a major limitation to accurate quantification of capture and use of resources such as water and nutrients. Inclusion of roots from another species may result in eco-morphological and eco-physiological changes in roots hence altering the efficiency of root function (Hauggaard-Nielsen and Jensen, 2005). Failure to adequately capture adaptive strategies for roots could result in inaccurate estimates of resource use. A major outcome of this was that, in order to improve current understanding of resource partitioning and use in intercrops, there is need to increase research on belowground interaction of intercrop systems.

The second objective of the review was to evaluate the extent of knowledge and gaps on modelling resource use in intercrop systems. It was evident that there are a limited number of models that can be used to simulate growth and resource use in intercrop systems. Most models were mechanistic and therefore, reductionist and complex. In the case of the former, crop models would explain the cropping system in terms of its individual constituent parts and their interaction and combine these to produce an output. Since individual constituent parts have to be defined, models, thus became complex since a large number of input parameters are required (Malézieux et al., 2009). It should be noted, however, increasing model complexity does not always increase accuracy of model prediction (Graves et al., 2002). This is considering that simpler empirical models have demonstrated high level of accuracy in simulating crop responses (Sinclair and Seligman, 2000). However, it has been

observed that complex models are more robust, that is, can simulate well over wide range of environmental conditions (Yin and Struik, 2010). This also explains why most intercrop models are mechanistic. That being said, model development for intercrop systems should also be as rigorous as development and model functionality of monocrops. Models for intercrop systems do not adequately capture below and aboveground canopy interactions as well as models used in monocrop simulations. For instance, most monocrop models can map our root water extraction pattern while reviewed model are to a large extent limited at doing this. Considering that current debate for sustainable farming systems is directed towards intercropping and other similar cropping systems, more investments are required in regard to intercrop modelling.

For the models reviewed, it was apparent that simulations of intercrop systems were governed by rationalism and assumptions. For instance, most models will rationalise by using conservative parameters such as RUE and WUE to describe biomass production. On the other hand, these very same models would assume that processes occurring at the organelle level, such as g_s or transpiration efficiency, are homogenous within leaf canopy; thus assume the big leaf approach (Friend, 2001). Rationalising and assuming parameters can give raise to inaccurate estimation of model responses thus leading to poor model performance. Nevertheless it was apparent that such assumptions within crop models were inevitable as assist in simplifying model parameterisation. In instances were multicrop models rationalism and assume a lot, performing sensitivity analysis could assist in identifying parameters sensitive to change. After which parameter calibration can done so as to improve accuracy of model simulation.

Use of bottle gourd within sorghum intercrop systems

Since the main objective of the study was to improve water use in sorghum systems, the agronomic potential for the inclusion of bottle gourd as another live mulch was determined through a review of literature. Bottle gourd is a versatile food crop and its growth habit makes it ideal to incorporate it as a live mulch for cover cropping (Chapter 3 and 4). Morphologically, bottle gourd has spreading veins with large broad leaves that enables it to

be an effective mulch as a cover crop. That being said, bottle gourd can be used to improve water use in intercropping systems. It was, however, revealed that seed quality is a major limiting factor to crop establishment. The significance of good seed quality stems from the advantages brought about by early establishment of an even crop stand. Good seed quality allows for good root growth and early attainment of canopy cover (Mabhaudhi et al., 2013; Chibarabada et al., 2015). Although, bottle gourd has agronomic potential as cover-crop it is underutilised. Few improved cultivars are available on the market and majority of rural farmers grow bottle gourd from retained seed of local landraces. The poor seed quality can result in poor establishment and a delay in canopy growth. This may result in a reduction in soil cover, thus resulting in an increase in soil evaporation; an unproductive use of water. It was observed that seed quality in bottle gourd was more of a function of provenance which also had a large effect on seed morphology.

To promote bottle gourd from its current status as an underutilised crop species to a commercially recognised crop, research needs to develop improved cultivars with good seed quality. This will aid in its acceptability as a cover crop within intercrop systems.

Resource use of sorghum intercrop systems

Considering that water applied was closely monitored, the inconsistency observed between water applied and soil water content across the water treatments could be due to differences in heights of water table relative to the soil surface. It could be that plots under rainfed were located in an area where there was a higher water table than plots under full irrigation. This resulted in higher soil water availability even with the application of less water. During site characterisation differences in the height of the water table were undetected and it was assumed that soil properties were heterogeneous within a reasonable limit to assume homogeneity for field management practices. Large experiments are often confounded by heterogeneity of land that cannot easily be dealt with by blocking and randomising. To improve management of water within water use studies, it is suggested that rigorous characterisation of a site must be carried out so as to avoid such discrepancies.

Photosynthetic capacity of a plant is governed by the ability to absorb and assimilate CO_2 into biomass (Lawlor, 2002). The observed response of physiological parameters, CCI and

gs, for sorghum under limited water availability showed that, even though the crop is drought tolerant, the photosynthetic capacity was down regulated so as to reduce accumulation of free radicles. In large amounts, these free radicles can impair many biochemical processes resulting in impaired photosynthetic activity due to damages rendered on thylakoid membranes, the site of PSII (Silva et al., 2015). While such down regulation occurs under normal conditions during peak transpiration demand, prolonged down regulation can lead to observations of reduced plant biomass and expansive growth. Down regulation of photosynthesis was also confirmed by the increase in specific leaf area (Chapter 4) under water limited conditions. Increase in SLA was attribute to reduction of leaf mass relative to its leaf area. Under water limitations, gs is often the first sign of stress while responses of CCI usually occur after prolonged exposure. With regards to sorghum, results of the study showed that gs was sensitive to changes in water fluxes. However, fluctuations were not as pronounced suggesting that sorghum was able to maintain a high g_s (standard deviation ±85 mmol m^{-2} m^{-1}) under different water availability. Sensitivity is not as pronounced as other cereal crops (Allen et al., 2011). For instance under water potential of -0.13 bars maize and sorghum gs was 63% and 38% lower as compared to under well water conditions (Niu et al., 2012). On the other hand, the known sensitivity of g_s to sudden changes in environmental conditions, especially diurnal, make it a less reliable parameter to use on its own in concluding on water stress. This is especially true for crops grown under irrigated conditions where periodic wetting and drying cycles are common. As such, measurements of g_s should be done during periods of soil drying (Mabhaudhi and Modi, 2013). It is suggested that parameters like CCI and SLA should be used together with g_s since their changes are more definitive responses to stress.

Intercropping sorghum with bottle resulted in reduction in photosynthetic capacity of sorghum relative to sole sorghum and sorghum intercropped with cowpea. It could be that, intercropping sorghum with bottle gourd resulted in a competitive interaction for N. This was consistent with low CCI and SLA observed (Chapter 3 and 4). Chlorophyll content index and SLA are both positively correlated with N concentration in the plant (An and Shangguan, 2008; Zhou et al., 2011). This suggests that, adding more than the recommended N for sorghum could minimise competition for the resource thus improve photosynthetic capacity of sorghum intercropped with bottle gourd. These results are largely speculative and need to

be validated in future studies. Then again, since results did not show any significant reduction on final yield, sorghum – bottle gourd systems can still be promoted in areas where soils are largely fertile.

The study showed that intercropping sorghum with either cowpea or bottle gourd increased resource use on a spatial scale. This follows through with literature evidence of increased resource use (Chimonyo et al., 2015). The observed results of LER, and increase in WUE and RUE suggest an overall facilitative interaction of sorghum with either cowpea or bottle gourd Jagatheeswaran and Walker (2014). Sorghum productivity was generally unaffected by intercropping while the added crop increased overall output per unit area. Therefore, intercrop system productivity was higher than sorghum sole crop system (Chapter 3). The observed response for sorghum was attributed to eco-physiological and eco-morphological responses which allowed the sorghum plant to accommodate the added crop. Therefore, we fail to reject the hypothesis that intercropping sorghum improves resource use and productivity especially in water limited conditions. In this regard, intercropping sorghum in semi-arid and arid regions should be promoted to improve productivity and water use.

Modelling resource use of sorghum intercrop systems

It was hypothesised that APSIM can be used to simulate performance of sorghum intercrops grown under rainfed conditions. For this study, the model APSIM was adapted for sorghum–cowpea intercrop system using soil and weather obtained from the field data while crop parameters were obtained from stress free sorghum and cowpea plots. Model performance was assessed using R^2, root mean squared error (RMSE) and its components (RMSEs and RMSEu) and the d-index. The model APSIM does not have a cucurbit crop file therefore only sorghum-cowpea intercrop system was modelled.

Overall, the model was able to simulate yield and water use of the intercrop system, however, it was limited in its ability to mimic canopy development. During model adaptation, there was over-estimation of LAI for both sorghum and cowpea while good simulations of biomass, yield and water use was observed. During model adaption, with the exception of RUE, default values of leaf parameters that affect leaf expansion and development such as SLA were assumed. In nature, the size of the canopy governs the use of resources, namely

radiation and water (Zhang et al., 2008; Picón-Toro et al., 2013). Canopy size is positively correlated to transpiration and radiation interception (Mabhaudhi et al., 2014). This was explicitly outlined and demonstrated in Chapters 2, 3 and 4. Failure to clearly define the canopy may result in incorrect estimations of resource use. This was shown by the over estimations of LAI but good simulation of biomass and yield. To improve the coherency for outputs of LAI, biomass and yield, a finer calibration of canopy parameters should be done.

During model testing, it was observed that the model showed good predictions for both sorghum and cowpea under DI and RF conditions for all traits simulated. Simulations were, however, not accurate under rainfed conditions. Model performance under rainfed conditions was negatively affected by intermittent wetting and drying that occurred especially during early vegetative development. This could have resulted in slight impairment of growth and productivity. These results are consistent with observed CCI and RWC reported in Chapter 2. To improve simulations under rainfed conditions, model sensitivity for simulating crop responses to water should be increased.

The objective of the scenario analysis was to use APSIM as a decision support tool for aiding the development of best management strategies for sorghum–cowpea intercrop system. I was hypothesised that APSIM was able to predict changes of yield and water use under different management scenarios. Based on this, we fail to reject the hypothesis, and state that indeed APSIM can be used as a tool to determine best management practices. It was observed that, while the categories of agronomic factors to be considered within the context of rainfed systems, there are a combination of best management options that could be prescribed to farmers across different climatic zones. Therefore, these findings suggest an agro-ecological based approach for managing intercropping and other cropping systems as well. Diversity in management practices insures flexibility towards climate uncertainty and increases resilience of the intercrop system. It was concluded that intercropping is an adaptive strategy that can be used to increase productivity. However, to further increase the system's resilience to climatic uncertainties, dynamic agronomic management practices should be adapted.

Conclusions

Despite the advantages of intercrop systems in resource utilisation and ultimately food production and security, conventional agronomic research has largely focused on monocrop systems. Our understanding of root interactions within intercrop systems is still limited and this has implications on interpretations of results on resource use. Representation of crop mixtures by models is also still restricted to a handful. There is need to increase the number of mechanistic models and enhance functionality of existing ones. However, this should not be at the expense of increasing model complexity since the utility and power of a model originates from its ability to simplify crop systems.

Bottle gourd is an ideal crop to include in improving water productivity under water limited conditions. However, there is still a dearth in knowledge pertaining to its agronomy within the context of semi-arid and arid regions. Seed quality is an important agronomic trait that can affect its use as a live mulch in intercrop systems. With the exception of seed size, morphological traits were not good indicators of seed quality. Larger seeds had better seed quality than small seeds. However, these results still need to be verified under sub-optimum conditions.

Under limited water availability, intercropping sorghum with either cowpea or bottle gourd resulted in more of a facilitative interaction with respect to water and radiation from physiological, growth and productivity perspective. Intercropping sorghum with cowpea and bottle gourd did not have any negative effect on growth, biomass production and partitioning and yield of sorghum. Cowpea and bottle gourd were able to improve soil water availability by minimising soil evaporation. Physiological parameters (g_s and CCI) proved to be useful indices for evaluating sorghum response to intercropping under limited water availability. On the other hand, LAI was a useful trait in assessing IPAR in that they were closely associated. Under RF conditions, intercropping improved overall productivity (LER), WU, WUE (biomass), radiation capture and RUE of sorghum cropping systems. There is need for future research on the root-shoot responses of intercropped sorghum to varying levels of water availability, focusing more on root interactions.

The APSIM model was able to simulate sorghum–cowpea intercrop system under different water regimes using a minimal set of inputs. Local adaptation of phenology and

RUE coefficients proved to be useful in improving model simulations under the different water regimes. The model gave reliable simulations of phenology, biomass, yield and crop water use for both sorghum and cowpea under DI and FI. The model was, however, limited in its ability to simulate under rainfed conditions. Simulations of biomass, yield and WU for sorghum–cowpea under rainfed conditions were overestimated and this resulted in a reduction of calculated WUEb. APSIM can be used to come up with viable irrigation management strategies for sorghum–cowpea intercrop systems and other intercropping systems alike. Therefore, the ability to model sorghum–cowpea intercrop system makes it a useful tool in assessing other intercrop systems. Furthermore, the study's' first attempt to model water use of sorghum - cowpea intercrop systems should also encourage modelling of ecologically based farming systems.

The model 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 was able to identify best management practices for improved water use efficiency for sorghum–cowpea intercrop under rainfed conditions. For environments included in this study, sorghum–cowpea intercrop system was most responsive to changes in planting dates and plant populations while moderate changes were observed in response to fertilisation 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.

Recommendations

Based on the observations made in this study, the following recommendations are given

    i.   Genetic assessment of bottle gourd should be carried within the region so as to establish diversity.

   ii.   Seed coat thickness of bottle gourd may be used as a parameter for recommending varieties into different agro-ecological areas. However, aspects of seed dormancy in conjunction with seed physiology as factors affecting seed quality warrants further investigation.

  iii.   Under low water availability, intercropping of sorghum, with particular reference to sorghum–cowpea intercrop system, should be recommended as a viable water management strategy as it has been shown to improve resource use on spatial scale.

  iv.   Agronomic recommendations for sorghum – bottle gourd intercrop system should be improved so as to include it as a food security strategy under water scarce conditions.

   v.   Any future studies of sorghum intercropping should include assessments of root interactions and possibly different plant populations and planting geometry as factors that might influence resource capture and use.

  vi.   To improve the estimation of IPAR for intercropped sorghum, a clumping factor must be considered in the calculation of intercepted radiation.

 vii.   The model should use a dual approach of both RUE and transpiration efficiency to calculate biomass so as to improve simulations under water scarce areas.

viii.   Improvements in model performance can be enhanced if the number of parameter inputs are increased. This increase its reliability and sensitivity, especially to sudden and extreme weather events.

  ix.   There is still need to apply APSIM to assess the effects of the combinations of these management options on yield and WUE for sorghum–cowpea intercrop system.

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