WATER USE OF SELECTED SORGHUM (*SORGHUM BICOLOR* L. MOENCH) GENOTYPES

Sandile Thamsanqa Hadebe

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Crop Science
School of Agricultural, Earth and Environmental Sciences
College of Agriculture, Engineering and Science
University of KwaZulu-Natal
Pietermaritzburg
South Africa

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Crop Science, School of Agricultural, Earth and Environmental Sciences, in the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa. The research was financially supported by the Water Research Commission (WRC) of South Africa through WRC Project No. K5/2272//4 'Determining water use of indigenous grain and legume food crops'.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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Signed: Professor Albert T. Modi

Date: 17 February, 2016

DECLARATION

I, Sandile T. Hadebe, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

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Signed: Sandile T Hadebe

Date: 17 February, 2016

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DEDICATION

This work is dedicated to all who cared and contributed to make both the researcher and research a success.

GENERAL ABSTRACT

Water scarcity is a major limitation to crop production in sub–Saharan Africa (SSA). Under these conditions, determining and predicting crop yield response to water in rainfed agriculture is useful for improving water productivity and food security. This study aimed to determine water use characteristics and water use efficiency of different sorghum genotypes as well as to model water use of such sorghum genotypes for extrapolation to other rainfed agro–ecologies. A review of water use of major cereal crops was conducted to gain insight into strategies to improve water productivity under arid and semi–arid agro–ecologies. To quantify water use and determine water use efficiency (WUE) of sorghum under different environmental conditions three sorghum genotypes, namely, PAN8816 (hybrid), Macia (open–pollinated) and Ujiba (landrace) were planted at two sites (Ukulinga and Mbumbulu) under rainfed conditions in 2013/2014 and 2014/15 seasons. Furthermore, PAN8816, Macia, Ujiba and IsiZulu (landrace) genotypes were planted at Ukulinga under early, optimal and late planting dates to determine sorghum water use characteristics (morphological, physiological, phonological and yield). Field trials planted at Ukulinga in 2013/14 were used to calibrate the AquaCrop model for PAN8816, Macia and Ujiba. Model testing was conducted using observations from three planting dates at Ukulinga during the 2014/15 season. Thereafter, PAN8816 and Ujiba crop files were used to use AquaCrop to extrapolate to other rainfed agro–ecologies in South Africa (Deepdale, Richard's Bay and Ukulinga) and develop best management recommendations for rainfed sorghum production. During the 2013/14 season, WUE was significantly lower at Mbumbulu (7.49 kg ha^{-1} mm^{-1}) relative to Ukulinga (11.01 kg ha^{-1} mm^{-1}). This was attributed to low total available water at Mbumbulu. Macia had higher WUE (10.51 kg ha^{-1} mm^{-1}) relative to PAN8816 (9.34 kg ha^{-1} mm^{-1}) and Ujiba (7.90 kg ha^{-1} mm^{-1}), however differences were not significant. During the 2014/15 season, sorghum genotypes adapted to low water availability through reduced canopy size and duration, low chlorophyll content index and stomatal conductance, as well as hastening phenological development. The AquaCrop model satisfactorily predicted yield response to water for the studied sorghum genotypes during calibration and testing. When applied for scenario analysis, the model performed well for the range of agro–ecologies considered. This study confirmed drought tolerance and high WUE of sorghum and it is concluded that sorghum is uniquely suitable and adapted to production under semi– and arid agroecologies of SSA. Furthermore, the study confirmed the use of the AquaCrop model as a cost–effective, relatively accurate tool to predict sorghum yield response to water.

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CHAPTER 1

GENERAL INTRODUCTION

1.1 Background and Introduction

Water availability is a major limitation to crop production in rainfed agricultural systems. Sub–Saharan Africa (SSA) comprises 43% arid and semi–arid area (FAO, 2008), which is projected to increase due to climate change. Small-scale, rainfed agriculture is the main livelihood source in arid and semi–arid areas of SSA. Since rainfed agriculture constitutes more than 95% of agricultural land use in SSA (Singh et al., 2011), water scarcity is a major limitation to crop production. Even in areas receiving adequate rainfall for crop production, rainfall can be highly erratic, unevenly distributed, with highly unpredictable onset and cessation of rainfall season (Chauvin et al., 2012). This makes crop water stress a common feature negatively impacting yields under rainfed farming. In SSA, challenges of water scarcity and food insecurity exist together. Increasing population, coupled with increasing competing demands for water by domestic and industrial sectors exerts added pressure on a resource that is already scarce. The fact that water is scarce means that increases in agricultural productivity have to be met without increases in water use. Under rainfed agriculture, this implies improving water use efficiency (crop output per given amount of water); this can be achieved by promoting cultivation of crop species that are water use efficient.

Agricultural systems in SSA are mainly cereal based, as such, cereal production constitutes a major portion of agricultural water use. Strategies to conserve water and improve crop water productivity in cereal production should seek to adapt cropping systems to low water availability. Inclusion and promotion of drought–tolerant cereal crops in rainfed cropping systems could potentially improve water productivity and contribute positively to food security. Sorghum uniquely fits production in such regions, due to its high and stable water use efficiency (WUE), drought tolerance, high germplasm variability, comparative nutritional value, and existing food value chain in SSA.

The challenge is to increase cereal crop water productivity under limited water resources. Sorghum, being a drought–tolerant cereal crop, has potential to address the twin challenges of increasing crop water productivity and contributing to food security in semi– and arid areas. Under rainfed agriculture, WUE is an accepted measure of crop water use. However, knowledge of sorghum WUE and water use characteristics is limited for SSA conditions and genotypes that are used by smallholders such as landraces. This knowledge would be valuable in fitting sorghum production into rainfed agro–ecologies and for developing recommendations for best production practices for farmers.

Examining yield response to rainfall amount and distribution under rainfed environments is both laborious and expensive. In consideration of such limitations, the use of crop models is a valuable prediction tool for yield response to water availability where environments, soils, genotypes and climatic conditions vary. One such predictive tool is AquaCrop. AquaCrop is a crop water productivity model developed by the Land and Water Division of FAO that simulates crop yield response to water (Steduto et al., 2009; Raes et al., 2009). It requires a relatively low number of parameters and input data to simulate yield response to water of most major field and vegetable crops. Its parameters are explicit and mostly intuitive and the model maintains sufficient balance between accuracy, simplicity and robustness (Steduto et al., 2009; Raes et al., 2009). AquaCrop predicts crop water productivity and water use efficiency of a wide variety of crops including cereals, and is particularly suited to address conditions where water is a key limiting factor in crop production.

1.2 Aims and objectives

This study aimed to determine water use characteristics and water use efficiency of different sorghum genotypes as well as to model water use of such sorghum genotypes for extrapolation to similar rainfed agro–ecologies. To address study aims, the following objectives were formulated:

(i) to conduct a comprehensive review on water use of cereal crops,

(ii) to quantify water use and determine water use efficiency of sorghum under different environmental conditions,

(iii) to determine water use characteristics (morphological, physiological, phenological, yield) of sorghum,

(iv) to calibrate and test AquaCrop for three sorghum genotypes, and

(v) to use AquaCrop to extrapolate to other rainfed agro–ecologies and develop best management recommendations for rainfed sorghum production.

1.3 Thesis Outline

In order to achieve the objectives of the study, a series of field and modelling studies were conducted. The separate studies are presented as individual manuscripts. In cases where the manuscripts have already been submitted to journals and are under review, the information is provided on the title page. An overview of the manuscripts that comprise this thesis is provided below:

Chapter 2: The chapter provides a review on water use of cereals in SSA. Key areas reviewed included production statistics, distribution, water use characteristics, WUE and projected impact of climate change. The review of literature provides justification for promotion and inclusion of sorghum as a drought–tolerant cereal in semi–arid and arid SSA regions and addresses objective (i) of the study.

Chapter 3: Reports on experimental trials to determine water use and WUE of landrace, open–pollinated variety and hybrid sorghum under rainfed conditions. This experimental chapter is linked to objective (ii) of the study. Crop parameters obtained from these field trials were used in calibrating the AquaCrop model (chapter 5).

Chapter 4: Sorghum genotypes were planted at different planting dates to determine water use characteristics of sorghum under variable rainfall conditions. This study investigated morphological, physiological, phenological, yield and water use responses of sorghum genotypes in response to varying planting dates. This experimental chapter is linked to objective (iii) of the study. Crop data obtained from these field trials were used to test the AquaCrop model (chapter 5).

Chapter 5: This chapter aimed to calibrate and test the AquaCrop for selected sorghum genotypes described in chapter 3 and 4. It addressed objective (iv) of the study. This was to evaluate model performance against observations under field conditions, and develop confidence in model application for application in later scenario analysis (chapter 6).

Chapter 6: following from successful calibration and testing of the model, AquaCrop was applied for extrapolating sorghum production to other rainfed agro–ecologies. This was meant to address objective (v) of the study.

Chapter 7: The last chapter provides a general discussion of the entire study by integrating the highlights of the separate manuscripts and addressing the overall study aim. It also provides recommendations for future studies.

CHAPTER 2

DROUGHT TOLERANCE AND WATER USE OF CEREAL CROPS: A FOCUS ON SORGHUM AS A FOOD SECURITY CROP IN SUB-SAHARAN AFRICA

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

Crop Science, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu–Natal, Private Bag X01, Scottsville 3209, Pietermaritzburg, South Africa

*Corresponding author at Crop Science, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu–Natal, Private Bag X01, Scottsville 3209, Pietermaritzburg, South Africa. Tel: +27332605447; Fax: +27332606094

Email address: hadebesta@gmail.com

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Abstract

Sub–Saharan Africa (SSA) faces twin challenges of water stress and food insecurity - challenges that are already pressing and are projected to grow. Sub–Saharan Africa comprises 43% arid and semi–arid area, which is projected to increase due to climate change. Small-scale, rainfed agriculture is the main livelihood source in arid and semi–arid areas of SSA. Since rainfed agriculture constitutes more than 95% of agricultural land use, water scarcity is a major limitation to production. Crop production, specifically staple cereal crop production will have to adapt to water scarcity and improved water productivity to meet food requirements. We propose inclusion and promotion of drought–tolerant cereal crops in arid and semi–arid agro–ecological zones of SSA where water scarcity is a major limitation to cereal production. Sorghum uniquely fits production in such regions, due to its high and stable water use efficiency, drought tolerance, high germplasm variability, comparative nutritional value, and existing food value chain in SSA. However, sorghum is socio–economically and geographically underutilized in SSA. Sorghum inclusion and/or promotion in arid and semi–arid areas of SSA, especially among subsistence farmers, will improve water productivity and food security.

Keywords: rainfed agriculture, water stress, small-scale farmers, water productivity, sorghum.

Introduction

Sub-Saharan Africa (SSA) has the highest percentage of food insecurity globally (Clover, 2003; FAO *et al*., 2014). Almost two out of every three people in SSA live in rural areas, relying principally on small-scale, rain-fed agriculture for their livelihood (FAO, 2013). In rural households, most food is produced and consumed locally (Garrity *et al*., 2010), making household agricultural productivity critical to improving food security (Schmidhuber and Tubiello, 2007). Rural poverty accounts for 83% of the total extreme poverty in SSA, and about 85% of the poor depend on agriculture for their livelihoods (Byerlee *et al*., 2005). Small-scale rainfed agriculture is the main livelihood source in arid and semi–arid areas of SSA. The yield levels in such farming systems are very low, especially during years of severe drought (Mavhura *et al*., 2015).

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

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

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

This review proposes sorghum as an alternative cereal crop for cultivation in SSA to enhance crop production and improve food security, especially in regions threatened by water scarcity. This article reviews water use of cereal crops produced in SSA and motivates for sorghum inclusion and/or promotion in arid areas of the region. This is done by reviewing cereal crop production in SSA, identifying agro-ecological zones (AEZs) and distribution thereof, identifying regions where inclusion and/or promotion of sorghum would benefit cereal production, and reviewing sorghum attributes which make it uniquely poised as a niche crop in such regions.

Water use of cereals

Distribution of agro–ecological zones and comparative advantage of cereals

Land and water resources and the way they are used are central to the challenge of improving food security across the world (FAO, 2011). Agriculture in SSA is 95% rainfed (Singh *et al*., 2011) with very limited use of external inputs such as fertilizers. This means that the land's agricultural production of cereals depends almost solely on the agro–ecological potential (Sebastian, 2009). Agro-ecological zones are geographical areas exhibiting similar climatic conditions that determine their ability to support rainfed agriculture. Sub–Saharan Africa can be divided into six AEZs, differentiated by the length of the potential growing period for rainfed agriculture. Within these AEZs, rainfall ranges dramatically, from over 2000 mm/year in central Africa to less than 400 mm/year in arid areas (Bationo *et al*. 2006; Ringler *et al*. 2010). These AEZs are: deserts, arid, semi-arid, humid, sub-humid and highland regions. Sub–Saharan Africa comprises 17% arid area, 17% semi-arid and 9% dry sub-humid, totaling 43% of the continent classified to an extent as arid (FAO, 2008). About 60% of SSA is vulnerable to drought, with 30% of it considered as highly vulnerable (Mavhura *et al*., 2015).

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

Cereal crop production in SSA

Sub–Saharan Africa's rural economy remains strongly agro–based relative to other regions (Livingston *et al*., 2011). As such, economic growth focused on agriculture has a disproportionately positive impact in reducing food insecurity. In SSA, cereals are a staple food for, and mostly produced by, resource-poor farmers. Cereals and cereal products are an important source of energy, carbohydrate, protein and fibre, as well as containing a range of micronutrients such as vitamin E, some of the B vitamins, magnesium and zinc (McKevith, 2004). Land under cereal production in SSA in 2008 was 92 132 298 hectares (World Bank, 2008). Cereal crops under production included: wheat, rice, maize, barley, oats, rye, millet, sorghum, buckwheat, teff and mixed grains (Haque *et al*., 1986; World Bank, 2008). The most widely cultivated cereal crops in SSA are maize, sorghum, millet and rice, respectively (Edmonds *et al*., 2009). Being the largest crop produced, maize has cultural, economic, and political significance in SSA and is the dominant staple food for much of eastern and southern Africa while greater dependence on millet, rice, and sorghum is found in western Africa (Doward *et al*., 2004).

Among the staple cereal crops, rice and maize have high water requirements (Table 1); hence production of cereal crops with low water requirements provides a comparative advantage in water scarce areas (Table 2). In large parts of SSA maize is the principal staple crop, covering a total of approximately 27 Mha. Maize accounts for 30% of the total area under cereal production in this region: 19% in West Africa, 61% in Central Africa, 29% in Eastern Africa and 65% in Southern Africa (FAO, 2010; Cairns *et al*., 2013). In Southern Africa, maize is particularly important, accounting for over 30% of the total calories and protein consumed (FAO, 2010). Among SSA AEZs, the sub-humid zone constitutes 38% of the total land area in SSA and has favourable rainfall (700-200 mm per annum) for maize production (Zingore, 2011). Maize yields have stagnated and in some areas declined in SSA. One of the primary reasons is lack of use of drought ameliorative measures (Fischer *et al*., 2014). This AEZ land area and rainfall is sufficient for production of maize and other high water requirement cereals lacking drought and heat tolerance. Rice lies fourth in area SSA area under production. In the decade, the growth of rice yield has dropped below 1% per year worldwide and low yield constitutes one of the main challenges of rice production in SSA. Rice production is increasingly constrained by water limitation and increasing pressure to reduce water use in irrigated production as a consequence of global water crisis (Zhang *et al*., 2012). Breeding attempts have resulted in Rice for Africa (NERICA) initiative, which has led to the release of upland NERICA varieties with relatively less water use compared to traditional lowland rice (Akinbile *et al*., 2007). However, even the NERICA varieties still have significantly higher water requirement and are still subject to extensive testing and drought evaluation (Matsumoto *et al*., 2014). Heat and drought stress usually occur concurrently (Rizhsky *et al*., 2002), hence lack of heat stress in NERICA rice remains a concern for production in arid and semi–arid SSA.

Table 1: Growing conditions, production statistics and water use characteristics of major cereals in SSA.

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

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

Table 2: Agro–ecological zones, their distribution in SSA and cereal crops with comparative advantage in each region.

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

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

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

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

Water use characteristics of cereal production in SSA

To improve cereal yield in arid and semi–arid AEZs, it is important to understand their crop water use. Under rainfed agriculture, water use efficiency (WUE) of major cereal crops becomes a key factor in increasing yield under water scarcity (Blum, 2005). Water use efficiency is defined and crop output (biomass and/or yield) obtained per given water use (evapotranspiration). Water use efficiency is a function of several factors, including crop physiological and morphological characteristics, genotype, planting population, soil characteristics such as soil water holding capacity, meteorological conditions and agronomic practices. In order to optimize yield under water limiting conditions, an ideal cereal crop should have a long and dense root structure, stay–green characteristics, high harvest index and maintain high WUE under stress. To improve WUE, integrative measures should aim to optimize cultivar selection and agronomic practices (Azizian and Sepaskhah, 2014).

Among the agronomic practices for improving WUE is crop selection. Multiple approaches have been proposed to improve cereal production in arid and semi–arid environments of SSA e.g. supplementary irrigation and breeding for drought tolerance in major crops (Ortiz *et al*., 2007; Edmeades *et al*., 2009; Kijne *et al*., 2009; Cairns *et al*., 2013). In this review, we propose production, promotion and inclusion of suitable drought–tolerant cereal crops to improve water use efficiency under arid and semi–arid AEZs of SSA. In comparison to teff and millet, sorghum has higher WUE (Table 1). Additionally, sorghum has the highest tonnage and number of SSA countries producing it. Lowest annual rainfall is experienced in arid and semi–arid AEZs of SSA. The situation is exacerbated by that received annual rainfall generally is not available throughout a crop's growing season (Table 2). Therefore, actual rainfall received during a growing season is often lower than quoted figures and also highly irregular. This makes sorghum production in arid and semi–arid regions of SSA a viable alternative (Table 2) for increasing water productivity in the region.

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

Impacts of climate change on cereal crop production

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

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

Sorghum adaptation to water stress

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

Physiological adaptation

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

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

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

Osmotic adjustment is conservation of cellular water content. In sorghum, osmotic adjustment is associated with sustained biomass yield under water-limited conditions across different cultivars (Blum, 2005). Osmotic adjustment helps maintain higher leaf relative water content at low leaf water potential under water stress; this sustains growth while the plant is meeting transpirational demand by reducing its leaf water potential (Blum, 2005). The osmotic potential is adjusted through changes in the accumulation of proline, inorganic ions, and other osmotic solutes (Sonobe *et al*., 2010). Increased deep soil water capture has also been found to be a major contribution of osmotic adjustment in sorghum (Blum, 2005). Typically in sorghum, older leaves are selectively senesced under stress, while the remaining young leaves retain turgor, stomatal conductance, and assimilation as a result of high osmotic adjustment in the younger leaves (Blum and Arkin, 1984). This ensures photosynthetic activity by keeping top leaves green, and reduced transpiration water losses by older shaded leaves under water stress. In addition, sorghum has an effective transpiration ratio of 1:310, as the plant uses only 310 parts of water to produce one part of dry matter, compared to a ratio of 1:400 for maize (Du Plesis, 2008). Hence production of sorghum in water scarce regions as an alternative to maize will conserve water and increase water productivity.

Morphological adaptation

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

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

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

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

Phenological adaptation

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

Water use efficiency

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

Sorghum daily water-requirements vary according to crop growth stage (Boyer, 1982; Abdel-Montagally, 2010), with maximal water requirement occurring from booting until after anthesis. Consequently, at this stage sorghum is most sensitive to water stress. During the grain filling stage, physiological maturity and senescence, water requirements decrease gradually. Maximum sorghum yield requires 450 to 650 mm of water distributed evenly over the growing season (Doorenbos and Hassam, 1979; Assefa *et al*., 2010). Sorghum grain yields are comparable to maize, and higher than those of other major cereals under optimal water availability (Table 2). Under water stress, sorghum produces more yield than other major cereals due to a superior WUE (Table 2). This reaffirms the fact that sorghum is a drought–tolerant crop capable of producing reasonable yields under water stress. Therefore, sorghum is uniquely poised as a niche crop in semi–arid and arid regions of SSA.

Sorghum nutritional value and utilization

Nutritional responses to water stress

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

Utilization, nutrition and health

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

Sorghum nutritional composition is comparable to other major cereals (FAO, 1995; Ragaee *et* al., 2006), which makes promotion and inclusion of sorghum in water scarce regions of SSA a good alternative from a nutrition standpoint. The average energy value of whole sorghum grain flour is 356 kcal per 100 g, which is comparable to other cereals (Table 3). Starch is the main component of sorghum grain, followed by proteins, non-starch polysaccharides and fat. The protein content in whole sorghum grain is in the range of 7–15% (Dicko *et al.,* 2006). The fat content, present mainly in the germ of the sorghum grain, is rich in polyunsaturated fatty acids, with a similar composition to maize fat. Sorghum is a good source of vitamins, mainly the B vitamins and the liposoluble vitamins A, D, E and K, and is a good source of more than 20 minerals including phosphorus, potassium, iron and zinc (Anglani, 1998; Glew *et al.,* 1997). Sorghum is important for human health in other respects. It is rich in fibre, bioactive compounds and antioxidant rich phytochemicals that are desirable in human health (Awika and Rooney, 2004; Dicko *et al.,* 2005; Dykes *et al.,* 2005; Rooney, 2007). Decreasing human consumption of sorghum in SSA (Sheorain *et al*., 2000; Adegbola *et al*., 2013) indicates that sorghum maybe underutilised in SSA despite comparable nutritional composition to major cereals.

Table 3: Grain nutrient composition (per 100 g at 12 percent moisture) of cereals.

	Protein	Fat	Ash	Crude fibre	Carbo–hydrate	Energy	Calcium	Iron	Thiamin	Riboflavin	Niacin
Cereals	(g)					(kcal)	(g)				
Rice	7.9	2.7	1.3	1.0	76.0	362	33	1.8	0.41	0.04	4.3
Wheat	11.6	2.0	1.6	2.0	71.0	348	30	3.5	0.41	0.10	5.1
Maize	9.2	4.6	1.2	2.8	73.0	358	26	2.7	0.38	0.20	3.6
Sorghum	10.4	3.1	1.6	2.0	70.7	356	25	5.4	0.38	0.15	4.3
Millet	7.7	1.5	2.6	3.6	72.6	336	350	3.9	0.42	0.19	1.1

(Sources: FAO, 1995; Dicko *et al.,* 2006).

Aspects of sorghum underutilization of in SSA

Whether sorghum in SSA is underutilized is a highly debated topic. This stems from the absence of a consensus definition for neglected and underutilized crop species (NUS). Neglected and underutilized crop species are generally referred to as those species whose potential to improve people's livelihoods, as well as food security and sovereignty, is not being fully realized because of their limited competitiveness with commodity crops in mainstream agriculture (Padulosi *et al*., 2011). Some NUS are highly adapted to marginal, complex, and difficult environments and contribute significantly to diversification and resilience of agro–ecologies (Chivenge *et al*., 2015). This means they are of considerable interest for future adaptation of agriculture to climate change and variability. It has been established that sorghum is adapted to water stress, and has comparable nutritional value and superior water use characteristics to major cereals. This makes it highly suited for current and future production in SSA to mitigate food security requirements in arid and semi–arid areas. However, it is vital to establish whether sorghum can be categorized as underutilized in SSA. If underutilized, then which aspects are underutilized and how can these be improved. This information will assist unlock the potential of sorghum for production is SSA.

A number of studies have described the typical features of NUS and the overriding issues affecting the conservation and use of their genetic resources (Padulosi *et al*., 1999; Williams and Haq, 2002; Padulosi *et al*., 2008; Galluzi and Lopez Noriega, 2014). Features commonly associated with NUS are: limited research efforts devoted to the species, limited representation of the species in globally available *ex situ* collections, limited representation of the species in national *ex situ* collections, limited efforts in germplasm characterization, limited knowledge of the species' distribution and production levels and lack of plant breeding efforts and commercial varieties of the crop species (Galluzi and Lopez Noriega, 2014).

Regarding typical features of NUS and the overriding issues affecting the conservation and use of their genetic resources, sorghum in SSA can be excluded from classification as underutilised. The existence of International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), large collections of germplasm collections and large scale production throughout the region disqualify sorghum on basis of such features. An estimate of 168,500 accessions (most of which are duplicates of the ICRISAT 36 774 world collection accessions) is contained in sorghum germplasm collections globally at multiple sorghum genetic resources conservation sites. The major organizations/countries which maintain sorghum genetic resources are the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh, India, the National Plant Germplasm System (NPGS) in USA, Ethiopia, Sudan, South Africa, India and China, primarily because they have large crop improvement programs (Rosenow and Dahlberg, 2000). Information on exact accession numbers held by these major organizations/countries is lacking, with the exception of ICRISAT. ICRISAT is a major repository for world sorghum germplasm with a total of over 36774 accessions from 91 countries. The collection is estimated to represent about 80% of the variability present in sorghum (Eberhart *et al*. 1997).

Landraces constitute 85.3%, breeding material 13.2%, wild species accessions 1.2% and named cultivars 0.3% of the total collection. Landraces and obsolete cultivars can be considered as a valuable portion of the gene pool because they represent the broad intra–specific genetic diversity of crops, therefore provides valuable characteristics important for breeding (Hermuth *et al*., 2010). This presents a breeding advantage over major cereals like maize, wheat and barley where the breeding material is below 10%. Tolerance to local stresses and the resulting good yield stability are also often referred to in landraces. The germplasm maintained at ICRISAT consists of five basic races: *bicolor, guinea, caudatum, kafir* and *durra* and their 10 hybrid races. Despite lagging behind many other commodity-based research programs, such as maize, sorghum research in SSA has been successful in diffusing a large number of new cultivars onto farmers' fields. The last two decades of research have resulted in the release of over 40 sorghum cultivars (Olembo *et al.,* 2010). However, rural–poor farmers who are the main constituency of sorghum farming in SSA still prefer landraces and may not have access to the diffused cultivars.

Advanced features used in determining whether a crop is underutilised are geographical distribution and socio–economic status. With regard to geographical distribution, a species could be underutilized in some regions but not in others. Regarding the socio–economic implication of the term, many species represent an important component of the daily diet of millions of peoples but their poor marketing conditions make them largely underutilized in economic terms. As such a crop can be widely cultivated across a region and still be underutilized.

Area under production of sorghum has increased in SSA. However sorghum yields in SSA have stagnated because production is being pushed into more marginal areas and poorer soils, even in areas that are already drought-prone (FAO and ICRISAT, 1996; Olembo *et al.,* 2010). Even in arid regions, maize remains the main crop under production (Table 4) when sorghum production confers a comparative advantage. Human consumption is decreasing with enhanced socio–economic status of population and easy availability of much preferred cereals in abundance and at affordable prices (Sheorain *et al*., 2000; Adegbola *et al*., 2013). The grain stands to contribute more to food security than at present, especially for in arid and semi–arid SSA (Adegbola *et al*., 2013) if promoted and included more in the cereal food value chain. Sorghum usage and food products are well established in the region (Berenji and Dahlberg, 2004), which should ease promotion of existing and development of new products. Sorghum in SSA is therefore socio–economically and geographical underutilized. High number and variation in germplasm, and existing food value chains eases promotion of sorghum as an alternative cereal crop under arid and semi–arid regions.

Table 4: Cereal production statistics in countries with arid and semi-arid AEZs in SSA.

Country	Country area [1,2] (1000 ha)	Agricultural area [1]	Cereal production area [1]	Ranking of 5 main cereals and area under production (1000 ha)[1]									
				1		2		3		4		5	
				Crop	Area	Crop	Area	Crop	Area	Crop	Area	Crop	Area
Botswana	58 173	25 920	146	A	870	B	500	C	580	–	–	–	–
B. Faso	27 422	11 770	4 210	B	1 807	C	1 327	A	9 136	D	139	–	–
Chad	128 400	49 932	2 542	B	850	C	800	A	300	C	205	E	17
Cameroon	47 544	9 750	–	A	832	B	800	D	167	C	70	E	1
Eritrea	11 760	7 592	440	B	250	C	55	F	45	E	25	A	20
Ethiopia	110 430	36 325	10 243	A	2 069	B	1 847	E	1 706	F	1 048	C	432
Kenya	58 037	27 430	2 494	A	2 028	B	189	E	313	C	88	D	30
Malawi	11 848	5 585	1 881	A	1 677	B	89	D	65	C	49	E	1
Mali	124 019	41 651	3 661	C	1 437	B	938	A	641	D	605	E	7
Namibia	82 429	38 809	276	C	230	A	28	B	16	E	2	–	–
Niger	126 700	44 482	10 242	C	7 100	B	3 100	A	15	D	13	E	2
Nigeria	92 377	71 000	17 545	B	5 500	A	5 200	C	4 000	D	2 600	E	80
Senegal	19 671	9 015	1 117	C	714	A	152	B	140	D	108	–	–
Somalia	63 766	44 129	398	B	270	A	124	E	3	D	1	–	–
S. Africa	121 909	96 374	3 993	A	3 250	E	520	F	80	B	60	G	27
Sudan	112 702	108 678	10 088	B	7 136	C	2 782	E	136	A	27	D	8
Tanzania	93 300	–	–	A	–	D	–	B	–	C	–	E	–
Zambia	75 261	23 636	1 145	A	998	E	42	D	39	C	34	B	23
Zimbabwe	39 076	16 400	1 379	A	900	C	230	B	230	E	10	F	< 1
Total				**A**	**4 907**	**B**	**4 125**	**C**	**2 687**	**D**	**1 175**	**E**	**1 159**
Africa				A	34 903	B	26 518	C	21 122	D	10 894	E	9 917

A= Maize, B = Sorghum, C = Rice, D = Wheat, E = Oats, and F = Barley.

(Sources: FAOSTAT, 2013 [1]; WDI, 2015 [2]). Note: Ranking of 5 main cereals and area under production in Eritrea and Ethiopia according FAOSTAT (2013) excludes teff, which is the main grain cereal under production (Yihun *et al*., 2013).

Conclusion

Sorghum is socio–economically and geographically underutilized in SSA. Sorghum production still lags behind maize even in arid and semi–arid AEZs where sorghum confers a comparative advantage. High WUE, adaptation to water stress, high germplasm variability, comparative nutritional value, and existing food value chain makes sorghum uniquely suited to improving cereal water productivity under water scarcity. How sorghum grain nutrients compare to that of other major cereals under water stress is unclear due to lack of NWP values for grain cereals. Rainfed cultivation of sorghum as an alternative to major cereals in arid, semi–arid and drought prone AEZs of SSA, and promotion of sorghum traditional and commercial food products can potentially improve food security in the region.

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CHAPTER 3

WATER USE CHARACTERISTICS OF LANDRACE, OPEN–POLLINATED VARIETY AND HYBRID SORGHUM UNDER RAINFED CONDITIONS

Sandile T. Hadebe, Tafadzwanashe Mabhaudhi, Albert T. Modi

S.T. Hadebe, T. Mabhaudhi, and A.T. Modi, Department of Crop Science, School of Agricultural Earth and Environmental Sciences, Univ. of KwaZulu-Natal, Pietermaritzburg, South Africa *Corresponding author (hadebesta@gmail.com).

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Abstract

Water use efficiency (WUE) is becoming a key issue in understanding the relationship between water availability and rainfed sorghum yields in rainfed agricultural systems across sub–Saharan Africa (SSA). The objective of this study was to determine water use of three sorghum varieties under different environmental conditions. Three sorghum varieties, a hybrid (PAN8816), a commercial open-pollinated variety (Macia) and a landrace (Ujiba) were planted at two sites (Ukulinga and Mbumbulu) during 2013/14 and 2014/15. Mbumbulu was characterized by low soil water availability. This resulted in significantly ($P<0.05$) low plant growth [leaf number, plant height and canopy cover (CC)] and physiology [chlorophyll content index (CCI) and stomatal conductance (SC)] relative to Ukulinga. Biomass and yield were also low under low soil water availability (Mbumbulu) relative to Ukulinga. Sorghum phenological development was hastened in Ujiba and PAN8816 under low soil water availability. Stay–green characteristics in Macia delayed phenological development. Macia and PAN8816 varieties demonstrated a delay in grain filling until conditions were favorable. Consequently, total and panicle WUE were, respectively, lower at Mbumbulu (14.93 and 7.49 kg ha^{-1} mm^{-1}) relative to Ukulinga (21.49 and 11.01 kg ha^{-1} mm^{-1}). Results showed that Macia had higher ($P<0.05$) WUE (10.51 kg ha^{-1} mm^{-1}) relative to PAN8816 (9.34 kg ha^{-1} mm^{-1}) and Ujiba (7.90 kg ha^{-1} mm^{-1}), respectively. Under low soil water availability, sorghum showed adaptation through leaf number, CCI, SC, and phenological plasticity. Lack of significant genotypic differences in yield and WUE efficiency highlights that all three varieties are equally suitable for production under sub–optimal conditions.

Keywords: water use efficiency, management practices, agro–ecologies, cereal crops

Abbreviations: SSA (Sub–Saharan Africa); WUE (water use efficiency); PAW (plant available water); CC (canopy cover); CCI (chlorophyll content index); SC (stomatal conductance).

INTRODUCTION

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

Drought stress is one of the most limiting factors for cereal crop yield. Drought and heat tolerance make sorghum unique among major cereal crops, suited for cultivation as staples in arid agro-ecological regions of SSA (Hattori et al., 2005; Staggenborg et al., 2008). It is the second most cultivated cereal crop in SSA and ranks first in the semi–arid Sahel (FAOSTAT, 2011). Although sorghum originated in SSA, where compared to major cereal crops, striking drought tolerance and superior WUE have evolved in the species, there is a need to harness these traits to positively contribute to food production, especially in arid and semi–arid regions. The available genetic resources in sorghum are still relatively under-exploited (Rosenow and Dahlberg, 2000; Kapanigowda et al., 2013). Rainfed sorghum farming systems differ in SSA. Sorghum is cultivated by both well-resourced commercial farmers, and resource-constrained smallholder farmers. The management practices under these two farming systems markedly differ, with high management practices by commercial farmers and low crop management by smallholder farmers. Crop management has implications on crop yield, hence WUE.

Crop production in SSA, specifically staple cereal crop production, needs to adapt to water scarcity and improve water productivity to meet food requirements. Sorghum's drought, heat and flood tolerance as well as high and stable WUE make it an ideal crop for production in SSA. However, studies of sorghum WUE and response of secondary traits associated with drought tolerance to water availability in rainfed agro-ecologies in SSA are lacking. This study investigated genotype-by-environment and water use characteristics of sorghum varieties.

Specific objectives were to: (i) determine morpho-physiological and phenological responses of three sorghum varieties to different agro-ecologies and management practices, (ii) determine yield responses of three sorghum varieties to different agro-ecologies, and (iii) to determine WUE responses for the three sorghum cultivars to different agro-ecologies and management practices.

MATERIALS AND METHODS

Plant material

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

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

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

Site description

Field trials were planted at two locations – Ukulinga (30°24'S, 29°24'E, 805 m a.s.l) and Mbumbulu (29°59'S, 30°42'E, 548 m a.s.l), South Africa, in 2013/14 and 2014/15. Ukulinga is a well-equipped agricultural research farm, whilst Mbumbulu is a resource–constrained rural setting. In addition, these two locations also offered two different micro-climates despite being classified under the same bioresource group (Table 1). Bioresource groups (BRGs), are defined as specific vegetation types characterized by an interplay of climate, altitude and soil factors.

Table 1: Bio–resource group classification, climate, and soil physical and hydraulic properties of Mbumbulu and Ukulinga planting sites.

Site	**Annual rainfall**	**Average temperature**	**Soil classification**	**Clay content**	**Field capacity**	**Permanent wilting point**	**Saturation**	**Soil profile depth**	**Saturated hydraulic conductivity**
	(mm)	(˚C)		(%)				(m)	(mm m^{-1} day^{-1})
Ukulinga	694	17.0	Vertisols	< 29	40.6	23	48.1	0.6	25.0
Mbumbulu	1009	17.9	Oxisols	> 60	45.1	34.5	51	1.5	79.7

Soil physical and hydraulic properties were obtained from classification and characterization of experimental site soils by Mabhaudhi (2012). These include: volumetric water content at field capacity (FC), at permanent wilting point (PWP), and at saturation (SAT), measured saturated hydraulic conductivity (K_{sat}), and soil depth (Table 1).

Trial layout and design

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

Data Collection

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

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

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

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

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

$$HI = Y/B \qquad \text{Equation 2}$$

where: Y = panicle mass, and

B = total above ground biomass

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

$$GDD = [(T_{max} + T_{min}) / 2] - T_{base} \qquad \text{Equation 3}$$

where: T_{max} = maximum daily temperature,

T_{min} = minimum daily temperature, and

T_{base} = base temperature below which sorghum growth ceases set at 7 °C (Du Plesis, 2008).

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

Crop water use

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

$$ET = I + P + C - D - R \pm \Delta SWC \qquad \text{Equation 4}$$

where: ET = evapotranspiration

I = irrigation added (mm),

P = rainfall (mm),

C = capillary rise (mm),

D = drainage (mm),

R = run-off, and

ΔSWC = change in soil water content.

Since trials were wholly rainfed, there was no irrigation (I) to be considered. Capillary rise (C) and drainage (D) were considered negligible (Ridolfi et al., 2008). Runoff (R) was also considered negligible in the soil water balance equation, due to sorghum rows orientated across the slope limiting runoff to negligible proportions. Therefore, Equation 4 was simplified to:

$$ET = P - \Delta SWC \qquad \text{Equation 5}$$

Water-use efficiency refers to the ratio of water used in plant metabolism to water lost by the plant through transpiration and soil evaporation (evapotranspiration). Water use efficiency was calculated for crops at physiological maturity using the following formula (Kuslu et al., 2010):

$$WUE = B / ET \qquad \text{Equation 6}$$

where: B = dry aboveground biomass (kg ha^{-1}), and

ET = actual field evapotranspiration (mm) obtained from Equation 5.

Agronomic practices

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

Soil samples were collected and analyzed for fertility before land preparation in both sites during both seasons prior to planting. A deficit of rainfed sorghum soil fertility requirements (112 kg ha^{-1}) as outlined in Smith, (2006) was applied at both sites using Gromor Accelerator® (30 g kg^{-1} N, 15 g kg^{-1} P and 15 g kg^{-1} K) slow release organic fertilizer, 14 days after sowing (DAS). At Ukulinga, 45 kg ha^{-1} and 48 kg ha^{-1} of fertilizer was applied; at Mbumbulu, 37 kg ha^{-1} and 34 kg ha^{-1} of fertilizer was applied for the first and second season, respectively. This was to meet nitrogen requirements of the soil, as this nutrient was observed as most deficient from soil sample analysis.

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

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

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

Data analyses

Measured crop parameters were subjected to analysis of variance (ANOVA) using GenStat® 16th edition (VSN International, Hemel Hemstead, UK). Tests for normality and homogeneity between planting seasons data were carried on Genstat to see if data should be analysed separately or in combination. Data was both normal and homogenous, meaning it could be analysed in combination. This allowed for comparison between data sets from two separate seasons. A general ANOVA was conducted, with the treatment structure of planting season by planting site by genotype. Means were separated using Fischer's protected least significant differences (LSD) at a probability level of 5%. Data analysis was not separated for each date but analysed as seasonal data.

RESULTS AND DISCUSSION

Seasonal and agro-ecological climate

Sorghum upper and lower temperature thresholds differ according to growth stage and agro–ecological region from which a cultivar is adapted. Upper (38°C) and lower (7°C) temperature thresholds for experimental varieties in this study were set according to local conditions (Huda et al., 1984; Du Plesis, 2008). Minimum and maximum temperatures did not exceed nor go below sorghum growing temperature thresholds at both planting sites in both seasons (Figure 1). This implies that crops did not experience heat or cold stress during both growing season at the two planting sites.

In descending order, rainfall received during the growing season (Table 2) was: second season in Mbumbulu (500.5 mm), second season at Ukulinga (401.25 mm), first season in Mbumbulu (294.90 mm), and first season at Ukulinga (226.09 mm). Seasonal rainfall was relatively higher at Mbumbulu than Ukulinga. However, the soil clay content at Mbumbulu exceeded 60%, and Ukulinga soils had less than 29% clay (Table 1). Root growth is limited by increased clay content in soils resulting in less soil water extraction by crops. Even worse, plant-extractable moisture in clay soils is somewhat less than the soil's physical properties alone would imply

(Whitmore and Whalley, 2009). This implies plant available water was relatively less than received rainfall in Mbumbulu compared to Ukulinga.

Table 2: Water use efficiency (WUE) water use characteristics at physiological maturity of three sorghum varieties planted at two planting sites over two growing seasons.

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

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

During the first growing season, rainfall became irregular and low (Figure 1) at both Ukulinga (post 70 DAS) and Whitmore Mbumbulu (post 105 DAS), which resulted in declining soil water content (Figure 2). This could have predisposed the crop to post–anthesis water stress, which has detrimental effects on grain filling and grain yield. Regular rainfall at both planting sites during the second season resulted in consistently high soil water content (Figure 2). While the soil water balance equation used in this experiment assumed negligible runoff, storm events at Ukulinga resulted in recorded rainfall events above the K_{sat} value (Table 1). This possibly resulted in run-off water losses and intermittent water logging of soils. In future, runoff curve numbers should be incorporated into the soil water balance to account for runoff. At Ukulinga, storms occurred 38 DAS in the first season and 104 DAS in the second season. Sorghum is tolerant to waterlogging (Promkhambut et al., 2011) hence intermittent waterlogging did not affect crop growth and development.

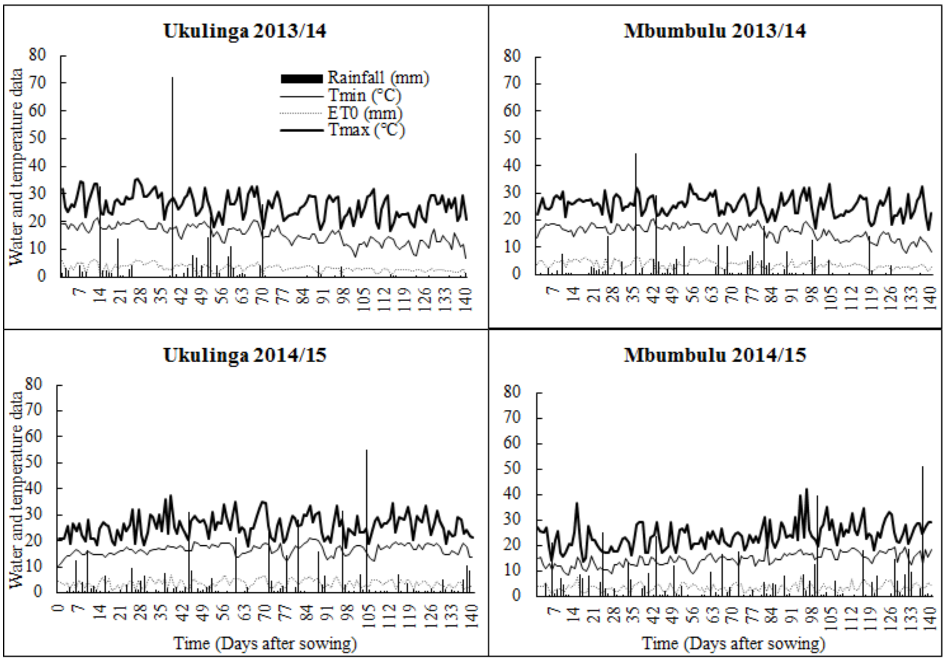

Figure 1: Daily rainfall, reference evapotranspiration (ETo), minimum (Tmin) and maximum (Tmax) temperature at Ukulinga and Mbumbulu during 2013/14 and 2014/15 growing seasons.

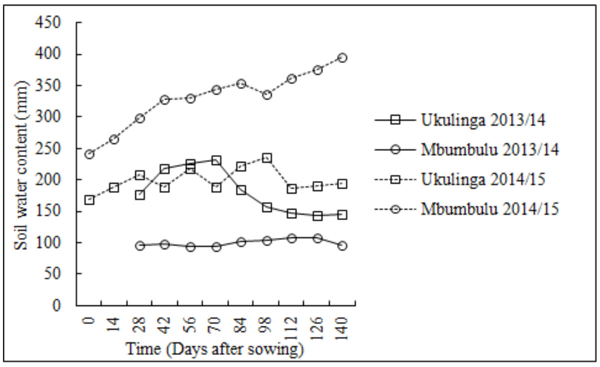

Figure 2: Biweekly soil water content measurements at Ukulinga and Mbumbulu during 2013/14 and 2014/15 growing seasons.

Crop morphology and physiology

The interaction between seasons, planting sites and varieties significantly ($P<0.05$) affected leaf number (Figure 3). Leaf number was affected ($P<0.001$) by season and site interaction. However, leaf number was statistically similar ($P>0.05$) among varieties. Mitosis and leaf appearance rate are turgor driven processes that are sensitive to plant available water. Despite relatively high rainfall at Mbumbulu compared to Ukulinga during each of the growing seasons, leaf number was lower in Mbumbulu. High soil water retention by the clayey soils at Mbumbulu decreased plant available water (PAW) and affected growth and development for all sorghum varieties. Under water stress, sorghum favors root growth at the expense of shoot and leaf growth (Hsiao and Xu, 2000) to increase soil water capture. Low plant available water at Mbumbulu therefore resulted in decreased leaf number. At both planting sites, seasons with low rainfall resulted in less leaf numbers.

Significant ($P<0.001$) genotypic variations were observed for plant height. With respect to maximum plant height, Ujiba was tallest (≈160 cm); Macia and PAN8816 were significantly shorter (≈120 cm) (Figure 4). PAN8816 and Macia have been bred as dwarf varieties; therefore, maximum height is genetically predetermined. The tall, Ujiba landrace was susceptible to lodging. Short varieties (Macia and PAN8816) were susceptible to panicle destruction by large birds (e.g. guinea fowls) as the head was within reach. Plant height of sorghum varieties differed significantly ($P<0.001$) between seasons and planting sites. Consistent with observations of leaf number, low soil water availability at Mbumbulu resulted in stunted plant growth. Cell division and expansion/elongation are both turgor driven processes hence the observed stunted growth at Mbumbulu (Farooq et al., 2009; Silva et al., 2014).

Achieving high canopy cover is important in reducing soil evaporation water losses and improving biomass production via maximizing transpiration (Mabhaudhi et al., 2013). Since transpiration is directly correlated to biomass, a larger canopy will translate to higher biomass and subsequently yield (Mabhaudhi et al., 2013). Canopy cover varied highly significantly ($P<0.001$) between seasons, planting sites and genotypes. Based on means of genotypes across seasons, high CC was observed at Ukulinga (57%) compared to Mbumbulu (32%) (Figure 5). This was consistent with low water availability and the stunted plant growth (leaf number and plant height) observed at Mbumbulu relative to Ukulinga. Based on means of genotypes for the two planting sites and seasons, CC was significantly higher ($P<0.001$) during the 2014/15 relative to 2013/14 planting season. This was attributed to conditions (temperature, rainfall and soil water availability) having been more favorable during the 2014/15 relative to the 2013/14 planting season. Canopy cover is a representation of plant canopy size (plant height, leaf number, leaf size and angle to the stem). In this instance, differences in leaf number accounted for differences in CC between seasons and planting sites. Based on means of planting sites and seasons, Macia had the lowest CC (41%) while PAN8816 (46%) and Ujiba (46%) had similar CC. This could be attributed to genotypic differences. PAN8816 is a hybrid and generally showed more vigorous growth. Ujiba had the same leaf number, taller plants but similar CC compared to PAN8816, hence it could be argued that Ujiba had smaller leaf size even though measurements of leaf size were not conducted.

Primary response of stomatal opening/ closure is to availability of soil water (Tombesi et al., 2015). Stomatal conductance was recorded for only the 2014/15 season. Results of SC in this study therefore have limited applicability. Sorghum varieties exhibited statistically similar (P>0.05) stomatal conductance across planting sites. However, SC was significantly lower (P<0.01) at Mbumbulu (189.6 $mmol.m^{-2}.s^{-1}$) than Ukulinga (291.7 $mmol.m^{-2}.s^{-1}$) (Figure 7). Primary response of stomata is to soil water availability. Under water stress, sorghum partially closes stomata to sustain reduced photosynthetic activity. Despite higher rainfall, low PAW in Mbumbulu compared to Ukulinga resulted in lower SC in Mbumbulu.

Chlorophyll content index was not significantly affected by the interaction of sites, seasons and varieties. However, CCI varied highly significantly (P<0.001) for planting sites and seasons. Chlorophyll content index was similar (P>0.05) among varieties. Mean values of planting sites across varieties showed that CCI for the two planting seasons were higher at Ukulinga (44.25 and 51.22) relative to Mbumbulu (34.98 and 41.67) (Figure 6). At each planting site, CCI increased with time. Variations in CCI between planting sites and seasons were consistent with observations that Ukulinga experienced less water stress than Mbumbulu, while 2014/15 was the more optimum season than 2013/14. In general, CCI is sensitive to water stress and will decline under water stress (Kapanigowda et al., 2013).

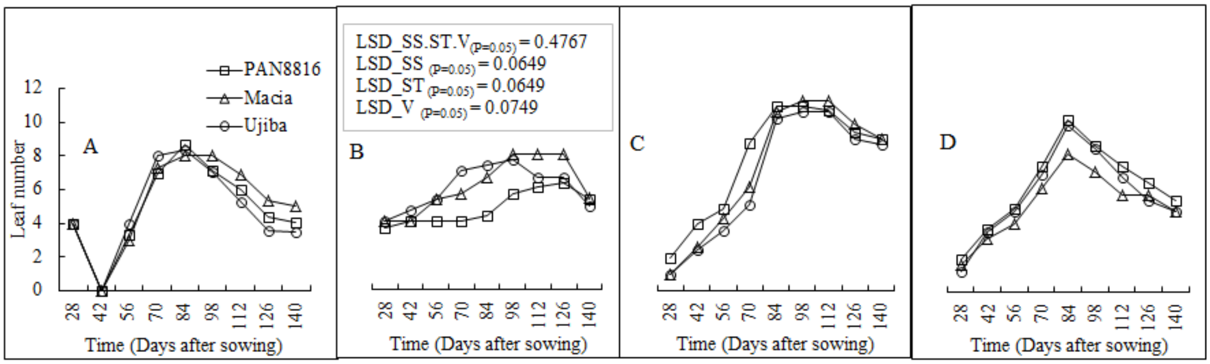

Figure 3: Leaf number in PAN8816, Macia and Ujiba sorghum varieties planted at Ukulinga (A and C) and Mbumbulu (B and D) during 2013/14 and 2014/15 growing seasons respectively. Note: SS.ST.V refers to the interaction between growing season (SS), planting site (ST) and sorghum varieties (V). SS refers to growing season, ST refers to planting site, while V refers variety. Means were separated by least significant values (LSD) at P= 0.05.

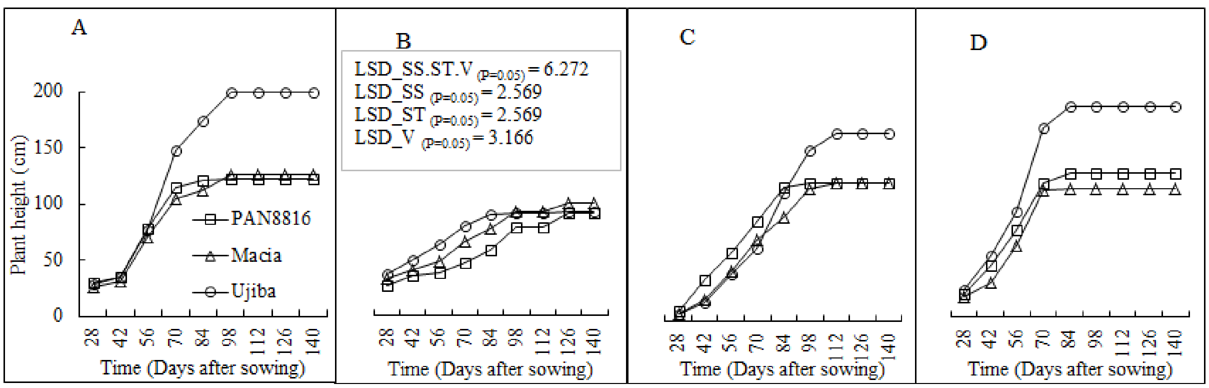

Figure 4: Plant height progressions in PAN8816, Macia and Ujiba sorghum varieties planted at Ukulinga (A and C) and Mbumbulu (B and D) during 2013/14 and 2014/15 growing seasons respectively. Note: SS.ST.V refers to the interaction between growing season (SS), planting site (ST) and sorghum varieties (V). SS refers to growing season, ST refers to planting site, while V refers variety. Means were separated by least significant values (LSD) at P= 0.05.

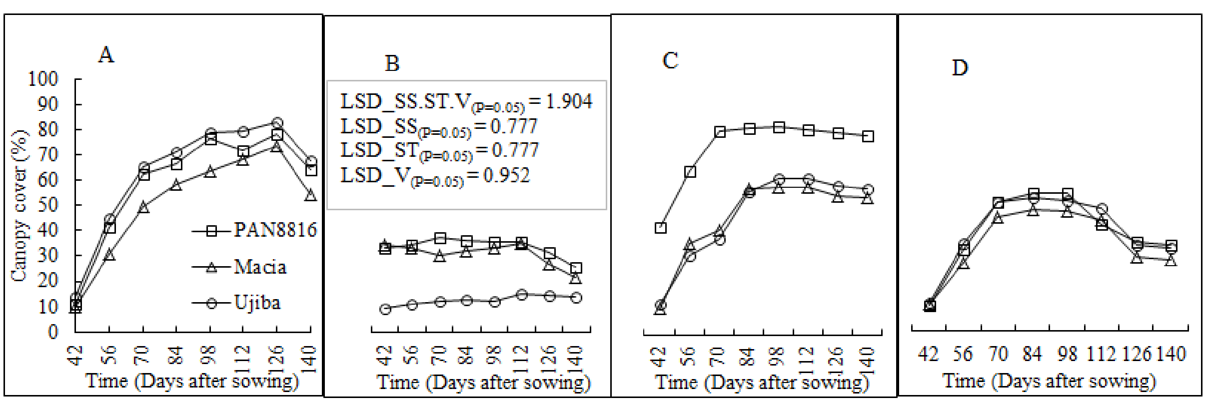

Figure 5: Canopy cover in PAN8816, Macia and Ujiba sorghum varieties planted at Ukulinga (A and C) and Mbumbulu (B and D) during 2013/14 and 2014/15 growing seasons respectively. Note: SS.ST.V refers to the interaction between growing season (SS), planting site (ST) and sorghum varieties (V). SS refers to growing season, ST refers to planting site, while V refers variety. Means were separated by least significant values (LSD) at P= 0.05.

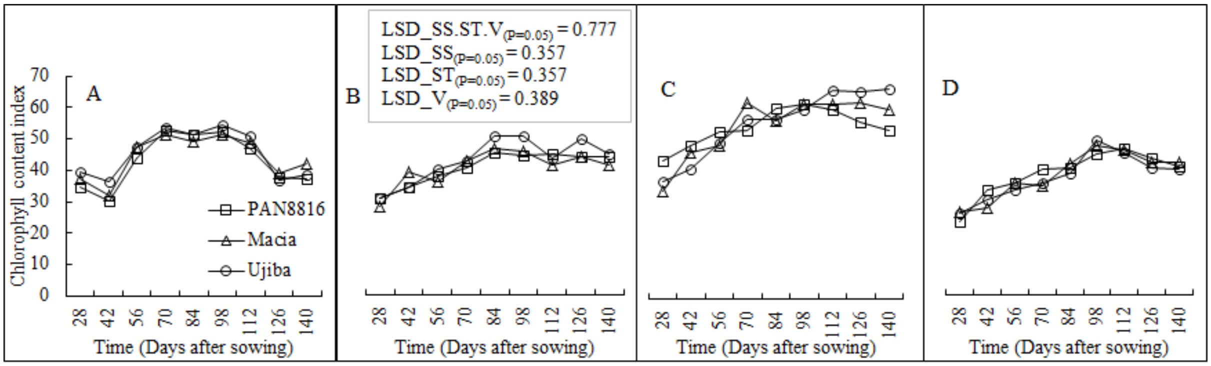

Figure 6: Chlorophyll content index in PAN8816, Macia and Ujiba sorghum varieties planted at Ukulinga (A and C) and Mbumbulu (B and D) during 2013/14 and 2014/15 growing seasons respectively. Note: SS.ST.V refers to the interaction between growing season (SS), planting site (ST) and sorghum varieties (V). SS refers to growing season, ST refers to planting site, while V refers variety. Means were separated by least significant values (LSD) at P= 0.05.

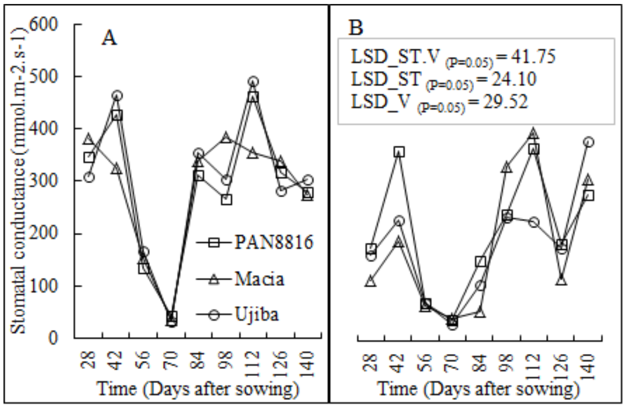

Figure 7: Stomatal conductance PAN8816, Macia and Ujiba sorghum varieties planted at Ukulinga (A) and Mbumbulu (B) during 2014/15 growing season. Note: ST.V refers to the interaction between planting site (ST) and sorghum varieties (V). ST refers to planting site, while V refers variety. Means were separated by least significant values (LSD) at P= 0.05.

Crop phenology

Results for phenological development are reported separately for Ukulinga and Mbumbulu, due to non–homogeneity of results (Table 3 and 4). At Ukulinga, on average, pre–anthesis phenological development occurred earlier for all varieties during 2013/14 compared to 2014/15 planting season (Table 3). This was because 2013/14 planting was associated with less rainfall and low soil water availability compared to the 2014/15 planting season which could be described as more favorable. Under low soil water availability, crop plants will often exhibit a shorter growth cycle as they try to escape drought (Mabhaudhi and Modi, 2013). Such drought escape and shortened growth cycle is also associated with low leaf number and reduced periods of canopy duration owing to early onset of canopy senescence (Mabhaudhi and Modi, 2013).

Table 5: Phenological development of three sorghum genotypes planted at Ukulinga during the first and second season.

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

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

Table 6: Phenological development of three sorghum genotypes planted at Mbumbulu during the first and second season.

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

Post-anthesis development and physiological maturity were delayed in all varieties in first season compared to the second season (Table 3). Low, irregular rainfall, and a consistent decrease in soil water content (Figure 2) potentially resulted in increased water stress. Sorghum utilises quiescence adaptive mechanisms to allow for extreme drought tolerance (Dugas et al., 2011), remaining dormant during drought conditions and only resuming growth once conditions are deemed favorable (Assefa et al., 2010). This is an important plant adaptation mechanism that ensures crop survival and yield under terminal stress thus almost assuring farmers of 'some' yield even under adverse conditions when other crops would fail. This could explain post–anthesis delays in time to reaching physiological maturity as a response to irregular and low rainfall. Despite early pre-anthesis development in PAN8816 compared to Ujiba, they both reached physiological maturity at similar times (133 DAS for first season, and 126 DAS during the second season), resulting in shorter grain filling period in Ujiba. Longer grain filling period can allow for increases in yield (Richards, 2000). Shorter grain filling period assures the crop of 'some' yield under water stress. Physiological maturity was latest in Macia, this led to extended grain filling period similar to that of PAN8816. Stay–green characteristics in Macia and PAN8816 allowed for delayed senescence and maturity even under irregular and low rainfall. Ujiba however hastened grain filling under water scarcity.

At Mbumbulu, all varieties reached crop establishment 14 DAS during both planting seasons. Pre–anthesis development occurred earlier in PAN8816 compared to Ujiba and Macia during the 2013/14 planting season (Table 4). However, all varieties reached physiological maturity at 140 DAS. Phenological development was similar for all varieties during the 2014/15 planting season.

Genotypic responses in dry biomass accumulation (Figure 8) and final biomass (Table 2) were not statistically different, also resulting in insignificant variations with respect to the interaction of planting sites, seasons and varieties. Sorghum has exceptional drought tolerance (i.e., ability to maintain high water tissue water status) which would have allowed for reduced but maintained photosynthesis under water stress (Blum, 2005). All sorghum varieties reduced leaf, number, CCI and SC in response to low water availability (Xu et al., 2010) in Mbumbulu. Mbumbulu dry biomass accumulation and final biomass was significantly lower than Ukulinga as a result, which highlights sorghum's adaptive mechanisms under conditions of low soil water availability. This also supported by its deep rooting which allows for enhance soil water capture. Biomass partitioning can be sensitive to water availability through phenological plasticity, manipulation of harvest index, and physiological adaption to water stress. This results in yield and biomass differences under different water availability conditions.

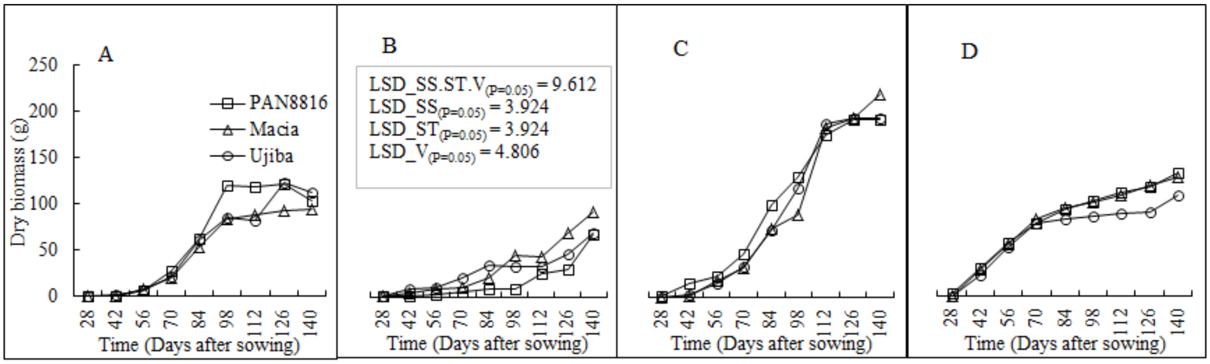

Figure 8: Destructively sampled dry aboveground biomass of PAN8816, Macia and Ujiba sorghum varieties planted at Ukulinga (A and C) and Mbumbulu (B and D) during 2013/14 and 2014/15 growing seasons respectively. Note: SS.ST.V refers to the interaction between growing season (SS), planting site (ST) and sorghum varieties (V). SS refers to growing season, ST refers to planting site, while V refers variety. Means were separated by least significant values (LSD) at P= 0.05.

Yield, water use and yield related components

Total panicle yield did not show significant interactions between sites, seasons and varieties. Panicle yield reduced in response to low water availability, resulting in significantly low panicle yield in Mbumbulu than Ukulinga site. Relatively low panicle yield was achieved in Ujiba landrace (2511.11 kg.ha^{-1}) compared to PAN8816 (3004.44 kg.ha^{-1}) and Macia (3515.56 kg.ha^{-1}), which highlights the advantage of breeding attempts in hybrids and OPVs. This was attributed to hastened grain filling stage in Ujiba in response to soil plant available water. Macia and PAN8816 seem to employ tolerance strategies towards post–anthesis water stress, whilst Ujiba employed escape strategies to ensure yield production under water stress.

Sorghum water requirements range from 450-650 mm (FAO, 1991; Hensley et al., 2000; Jewitt et al., 2009). Measured crop water use was below reported water requirements for all seasons, varieties and planting sites (Table 2). This was directly linked to low rainfall (Table 2), implying that water was limiting to crop production. Under sub–tropical, rainfed agriculture, optimal sorghum WUE is reported to be 12.4 – 13.4 kg ha^{-1} mm^{-1} (Maman et al., 2003). In this study, sub-optimal plant water availability resulted in sub–optimal WUE. On the contrary, Abdel-Montagally

(2010) found maximal WUE under sub–optimal water availability due to sustained biomass production under significantly low plant available water. Findings of the present study are in agreement with Tres et al., (2010), who reported low WUE under sub-optimal water availability in wheat, rice, maize and sorghum. Differences in genotypes used, duration and extent of water scarcity accounted for disagreement of results in this study with those of Abdel-Montagally (2010). Total and panicle WUE were respectively lower ($P<0.05$) at Mbumbulu (14.93 and 7.49 kg ha^{-1} mm^{-1}) relative to Ukulinga (21.49 and 11.01 kg ha^{-1} mm^{-1}). Macia had higher ($P>0.05$) WUE (10.51 kg ha^{-1} mm^{-1}) relative to PAN8816 (9.34 kg ha^{-1} mm^{-1}) and Ujiba (7.90 kg ha^{-1} mm^{-1}), respectively. Smallholder farmers can afford to continue cultivating Ujiba as the yield disadvantage is minimal under rainfed agriculture. Results were inconclusive towards yield and WUE genotypic responses at optimal water availability. This would assist genotype selection under a range of water availability.

CONCLUSION

This study showed significant differences between genotypes as well as environments. Mbumbulu was characterized by low soil water availability. This resulted in significantly ($P<0.05$) low plant growth [leaf number, plant height and canopy cover (CC)] and physiology [chlorophyll content index (CCI) and stomatal conductance (SC)] relative to Ukulinga. Biomass and yield were also low under low soil water availability (Mbumbulu) relative to Ukulinga. Sorghum phenology was hastened in Ujiba and PAN8816 under low soil water availability. Stay–green characteristics in Macia delayed phenological development. Macia and PAN8816 varieties demonstrated dormancy in terms of delaying grain filling until conditions were favorable. Consequently, total and panicle WUE were respectively lower at Mbumbulu (14.93 and 7.49 kg ha^{-1} mm^{-1}) relative to Ukulinga (21.49 and 11.01 kg ha^{-1} mm^{-1}). Despite insignificant genotypic differences in WUE, Macia had higher ($P>0.05$) panicle WUE (10.51 kg ha^{-1} mm^{-1}) relative to PAN8816 (9.34 kg ha^{-1} mm^{-1}) and Ujiba (7.90 kg ha^{-1} mm^{-1}), respectively. Under low soil water availability, sorghum showed adaptation through leaf number, CCI, SC, and phenological plasticity. Lack of significant genotypic differences in yield and WUE efficiency highlights that all three varieties are equally suitable for production under sub–optimal conditions. Studies using multiple rainfed agro–ecologies of SSA are required to conclude on water use, yield and WUE of sorghum varieties across SSA. Long term weather data and analysis of rainfall distribution in relation to crop water use requirements at different growth stages would be valuable for knowledge of how water availability affects yield and WUE in rainfed sorghum. Due to feasibility constraints, the use of crop models to extrapolate water use and yield potential of sorghum genotypes under rainfed agriculture is imperative.

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CHAPTER 4

WATER USE OF SORGHUM (*SORGHUM BICOLOR* L. MOENCH) IN RESPONSE TO VARYING PLANTING DATES

*Sandile T. Hadebe, Tafadzwanashe Mabhaudhi and Albert T. Modi

Crop Science, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu–Natal, Private Bag X01, Scottsville 3209, Pietermaritzburg, South Africa; Tel: +27332605447; Fax: +27332606094; Corresponding author email: hadebesta@gmail.com.

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ABSTRACT

It is vital to understand how rainfall onset, amount and distribution between planting dates affect sorghum yield and water use in order to aid planting date and cultivar selection. This study investigated morphological, physiological, phenological, yield and water use characteristics of different sorghum genotypes in response to different planting dates**.** Four genotypes [PAN8816 (hybrid), Macia (open–pollinated variety, OPV), Ujiba and IsiZulu (both landraces) were planted at three planting dates (early, optimal, and late) in a split–plot design, with planting dates as the major factor. Low soil water at the optimal planting date was associated with delayed crop establishment and low final emergence. Sorghum genotypes adapted to low and irregular rainfall at the late planting date through low leaf number, canopy cover, chlorophyll content index and stomatal conductance, and hastening phenological development. This resulted in low biomass and yield. Landraces exhibited panicle yield stability across planting dates, whilst OPV and hybrid genotypes significantly reduced panicle yield in response to low water availability when planted late. This resulted in significantly higher yield in landraces compared to OPV and hybrid genotypes at the late planting date. Biomass and yield water use efficiency (WUE) were highest at optimal planting (30.5 and 12.2 kg ha^{-1} mm^{-1}), relative to late (23.1 and 11.8 kg ha^{-1} mm^{-1}), and early planting dates (25.2 and 10.9 kg ha^{-1} mm^{-1}). For the hybrid and OPV, biomass and yield WUE decreased in response to low soil water content, and irregular and disproportionate rainfall experienced during the late planting date. By contrast, biomass and yield WUE for the landraces improved with decreasing rainfall. Hybrids are recommended when planting under low soil water availability to maximize crop stand. Cultivation of OPVs is recommended under optimal conditions. Landraces are recommended for low rainfall areas with highly variable rainfall.

Abbreviations: SSA (sub–Saharan Africa); OPV (open–pollinated variety); CC (canopy cover); CCI (chlorophyll content index); SC (stomatal conductance); WUE (water use efficiency), HI (harvest index); TAW (total available water); and SWC (soil water content).

Keywords: planting dates, water use efficiency, rainfall variability, water use, cultivar selection.

INTRODUCTION

Sub-optimal availability of water for unrestricted plant growth and transpiration, i.e., drought, is a major limitation to agricultural production (Delmer, 2005). Rainfall can be erratic and irregular in sub–Saharan Africa (Chauvin et al., 2012) where climate variability mainly impacts resource-poor farmers, whose livelihoods depend mainly on rainfed agriculture (Tadross et al., 2005). The inability of this group of farmers to adapt to changing or variable weather patterns makes them increasingly vulnerable and prone to repeated episodes of crop failure and food insecurity. For farmers relying on rainfed agriculture, the ability to adapt to changing weather patterns on a season-to-season basis is thus a prerequisite to successful crop production. There are various strategic and tactical decisions that can allow for farmers to adapt to changing and variable weather patterns. On a tactical level, these include crop or cultivar choice and planting date selection.

Traditionally, farmers use the onset of the rainy season as the criteria for setting planting dates. Multiple planting dates can occur in a single rainy season depending on onset and longevity of rainfall season, and crop growing period. The instability in rainfed production is largely credited to availability of rainwater, which itself shows wide variability in both total amounts and seasonal quality (Rockström and Barron, 2007). False planting dates can result in crop failure, usually requiring replanting or reduced yield as a consequence of unmet water requirements. Crops adapt to diverse environments through considerable plasticity of phenology, morphology and physiology, the main determinant of which is rainfall (Udungwu and Summerfield, 1985). One of the ways of manipulating the climatic factor is adequate knowledge of optimal planting dates so as to accurately synchronize rainfall incidences with the agricultural calendar of crops (Adetayo et al., 2008).

Sorghum is an ideal crop with high tolerance to many types of stresses, including temperature, water and salt stresses (Ejeta and Knoll, 2007). The Department of Agriculture and Forestry (DAFF, 2010) recommends optimal planting time of sorghum from start of November until end of December in South Africa, with dates falling on either side of the recommended times regarded as early and late planting, respectively. The first sowing date can be defined as the first rainfall event capable of supporting germination (Keatinge et al., 1995). Delays in onset of rainfall, drought seasons, unpredictable periodic dry spells and lengthened rainfall season have shifted traditionally recommended sorghum planting dates. Knowledge of cultivar performance under different planting dates in SSA is lacking for mitigation and production plasticity under different planting date scenarios. Characterising crop water use responses for sorghum as an alternative staple cereal crop in dryland farming under different planting dates therefore has positive implications for food security. This study investigated morphological, physiological, phenological, yield and water use characteristics of different sorghum genotypes in response to different planting dates under dryland farming**.** It was hypothesised that crop water use responses of different sorghum genotypes would not differ given different planting dates.

MATERIALS AND METHODS

Plant Material

Four genotypes of sorghum were used, namely PAN8816, Macia, Ujiba and IsiZulu (*imbewu yesiZulu*). PAN8816 was sourced from Pannar Seeds. It is a bronze–grained, medium to late maturing, low–tannin hybrid renowned for leaf disease and head smut resistance. Flowering occurs approximately 71 days after sowing. Macia is an early to medium maturing (60–65 days to floral initiation and 115–120 days to maturity), semi dwarf (1.3–1.5 m tall with thick stem), low–tannin open–pollinated variety. It has good drought tolerance (250–750 mm rainfall range during the growing season), with stay green characteristics extending beyond harvest. Yield potential is 3–6 t ha^{-1}. Ujiba is a reddish-brown seeded, tall growing (>1.5 m), high–tannin landrace genotype sourced locally from smallholder farmers in Tugela Ferry (28°44'S, 30°27'E). IsiZulu is a dark-brown seeded, tall growing (> 1.5 m), high–tannin landrace genotype sourced locally from smallholder farmers at Nkandla (28°50'S, 31°06'E). For landraces, phenological, morphological and physiological information was lacking.

Site Description

Field trials were planted at Ukulinga Research Farm (30°24'S, 29°24'E, 805 m a.s.l) on 03 November 2014, 17 November 2014, and 26 January 2015. The farm is situated in Mkhondeni, in Pietermaritzburg in the subtropical hinterland of KwaZulu-Natal province. Ukulinga represents a semi-arid environment and is characterised by clay-loam soils (USDA taxonomic system). Rain falls mostly in summer, between September and April. Rainfall distribution varies during the growing season (Swemmer et al., 2007) with the bulk of rain falling in November, December and early January. Occasionally light to moderate frost occurs in winter (May – July).

Trial Layout and Design

The experimental design was a split–plot design with planting date as the main factor and genotypes as the sub–factor laid out in randomised complete blocks with three replicates. The planting (03 November 2014, 17 November 2014, and 26 January 2015) represented early, optimal and late planting dates for sorghum. Early planting reflected onset of rainfall season at Ukulinga. Optimal planting date was based on DAFF (2010) recommendations and historical weather data at Ukulinga. Late planting date represented latest planting from which seasonal rainfall can sustain 120–140 day growing season. The trials comprised four sorghum cultivars, namely: PAN8816, Macia, Ujiba and IsiZulu. Main plot size was 310 m^2. Sub–plot size was 6 m * 4.5 m (18 m^2), with 1 m interplot spacing between the plots. Inter-row spacing was 0.75 m with 0.30 m intra-row spacing, amounting to 21 plants per row and 63 experimental plants per plot. Each individual plot had seven rows with the three inner most rows as the experimental plants, and the remaining rows reserved for destructive sampling. Planting rows were dug ≈25 mm deep, seeds were sown closely and thinned to the desired crop density after establishment.

Data Collection

Atmospheric data

Daily data for meteorological parameters was obtained from an on–station (within 100 m radius) automatic weather station courtesy of the Agricultural Research Council – Institute for Soil, Climate and Water (ARC–ISCW). Data collected included minimum and maximum temperature, rainfall, maximum and minimum relative humidity, wind speed and direction, solar radiation and reference evapotranspiration.

Soil characterisation

The soil textural class was described as clay (USDA Taxonomic System). Soil physical and hydraulic properties were obtained from classification and characterisation of experimental site soils by Mabhaudhi (2012). These included volumetric water content at field capacity (FC), permanent wilting point (PWP), and saturation (SAT), as well as saturated hydraulic conductivity (K_{sat}), total available water (TAW) and soil thickness (Table 1).

Table 1: Soil physical and hydraulic properties from Ukulinga experimental site (Mabhaudhi, 2012).

Texture	Bulk density	Permanent wilting point	Field capacity	Total available water	Saturation	Saturated hydraulic conductivity
	($g.m^{-3}$)			($mm.m^{-1}$)		($mm.m^{-1}.day^{-1}$)
Clay	1.20	283.00	406.00	123.00	481.00	25.00

Crop data

Seedling emergence was considered as coleoptile protrusion above soil surface. Weekly emergence was scored from sowing until establishment (90% emergence). Plant height was measured weekly from establishment using a tape measure as distance from soil surface to the tip of the youngest developing leaf (before floral initiation) or tip of the growing panicle thereafter. Leaf number was counted for fully expanded and photosynthetically active (50% green leaf area) leaves from establishment (Mabhaudhi and Modi, 2013). A fully formed leaf was defined as when the leaf collar was visible without dissecting the plant. The flag-leaf was counted as the first leaf upon full formation. Canopy cover (CC) was measured using the LAI2200 canopy analyser (Li–Cor®, USA). Values describing the diffuse non-intercepted radiation (DIFN) which is the amount of light visible below were taken and converted to percentage canopy cover as described by Mabhaudhi et al. (2014):

$$CC = (1 - DIFN) \times 100\% \quad \text{Equation 7}$$

Chlorophyll content index (CCI) was measured using a SPAD-502 *Plus* chlorophyll meter (Konica Minolta, Osaka, Japan) on the adaxial surface of the first fully expanded, fully exposed leaf weekly at midday. Stomatal conductance (SC) was measured weekly at midday using a SC-1 leaf porometer (Decagon Devices®, USA) from the abaxial surface of the first fully expanded, fully exposed leaf.

Yield and yield related parameters

Aboveground dry mass was recorded as the average of two destructively sampled plants per plot. Biomass was recorded as sorghum dry shoot and fruit mass (aboveground marketable biomass) weekly after crop establishment (90% emergence). Starting at flowering (complete panicle exposure), panicle mass and total above ground above biomass were weighed separately to enable calculations of build-up of harvest index (HI). After which, harvest index was calculated as follows:

$$HI = Y / B$$ Equation 8

where: Y = panicle mass, and

B = total above ground biomass

Total biomass, yield and HI were measured at physiological maturity. Thousand seed mass was measured from a random sample of a thousand, dry (<12.5% moisture content) seeds per genotype at harvest.

Phenology

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

$$GDD = [(T_{max} + T_{min}) / 2] - T_{base}$$ Equation 9

where: T_{max} = maximum daily temperature,

T_{min} = minimum daily temperature, and

T_{base} = base temperature below which sorghum growth ceases set at 7°C.

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

Crop Water Use

Soil water content (SWC) was measured every week using a PR2/6 profile probe (Delta–T, UK). Weekly measurements of SWC were then used to compute a soil water balance (Zhao et al., 2004) as follows:

$$ET_a = I + P + C - D - R \pm \Delta SWC$$ Equation 10

where: I = irrigation added (mm),

P = rainfall (mm),

C = capillary rise (mm),

D = drainage (mm),

R = run-off, and

ΔSWC = change in soil water content.

Since trials were wholly rainfed, there was no irrigation (I) to be considered. Capillary rise (C) and drainage (D) were considered negligible (Ridolfi et al., 2008; Gregory and Northcliff, 2012). Runoff (R) was also considered negligible in the soil water balance equation, due to sorghum rows orientated across the slope limiting runoff to negligible proportions. Therefore, Equation 4 was simplified to:

$$ET = P - \Delta SWC \qquad \text{Equation 11}$$

Water-use efficiency refers to the ratio of water used in plant metabolism to water lost by the plant through transpiration and soil evaporation (evapotranspiration). Water use efficiency was calculated for crops at physiological maturity using the following formulae (Kuslu et al., 2010):

$$WUE = B / ET \qquad \text{Equation 12}$$

where: B = dry aboveground biomass (kg ha^{-1}), and

ET = actual field evapotranspiration (mm) obtained from Equation 5.

Growth stages (initial, development and mid–season) were defined according to FAO (1986), and were used to calculate cumulative rainfall received during each stage. Rainfall received for the late season was not considered as crop development was observed from sowing to physiological maturity instead of until harvest maturity.

Agronomic Practices

Soil samples were collected and analysed for fertility before land preparation. Before planting, fallow land was mechanically ploughed, disked and rotovated. A pre-emergence herbicide, Round-up® (10 mℓ per 1ℓ of water) of which glyphosphate is the active ingredient, was applied to control weeds two weeks before planting. A deficit of fertilizer requirements (Smith, 2006) as per soil analysis observation prior to planting was applied using Gromor Accelerator® (30 g kg^{-1} N, 15 g kg^{-1} P and 15 g kg^{-1} K), a slow release organic fertilizer at 14 days after sowing (DAS). Planting rows were opened by hand 25 mm deep and seeds were hand-sown in the ground. Planting was conducted by drilling sorghum seeds. Thereafter, at crop establishment (14 DAS), seedlings were thinned to the required spacing. Scouting for pests and diseases was done weekly. Cypermethrin® (15 mℓ per 10 ℓ knapsack) was applied to control insect pests one month after planting. Weeding was done using hand-hoes at frequent intervals.

Data Analyses

Recorded crop parameters were subjected to analyses of variance (ANOVA) using GenStat® 16th edition (VSN International, UK). Means were separated using least significant differences (LSD) at a probability level of 5%. Multiple comparisons between means were conducted using Fisher's protected LSDs. Data analysis was not separated for each date but analysed as seasonal data.

RESULTS AND DISCUSSION

Crop responses to rainfall, temperature and evapotranspiration

In South Africa, Du Plesis (2008) reported that, for sorghum, the lower temperature threshold limit was 7°C while the upper temperature threshold limit for sorghum grown in semi-arid tropics has been reported as 38°C (Huda et al., 1984). Hence 38°C and 7°C upper and lower temperature thresholds, respectively, were adopted for experimental genotypes in this study. Minimum and maximum temperatures neither exceed nor went below sorghum growing temperature thresholds during the growing season for the early and optimal planting dates. This implies that crops did not experience heat or cold stress (Figure 1). This was confirmed by lack of heat stress symptoms such as scorching of leaves and stems, premature leaf abscission and senescence, shoot growth inhibition or fruit damage (Vollenweider and Günthardt-Goerg, 2005). For late planted sorghum, minimum temperatures dipped below minimum thresholds at 130 DAS (Figure 1). However, such cold stress coincided with physiological maturity in sorghum, making the effect on plant growth negligible. Temperatures were relatively low for late planting compared to early and optimal.

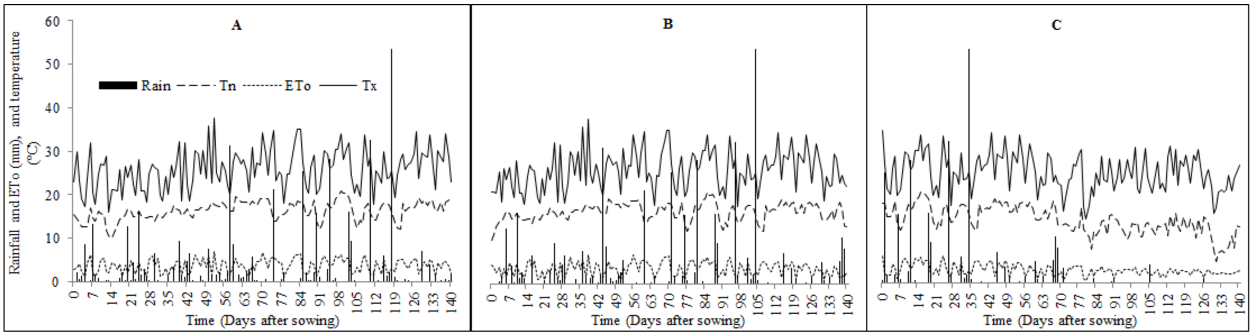

Figure 1: Daily reference evapotranspiration (ET_o), minimum temperature (Tn), maximum temperature (Tx), and rainfall during the growing seasons of early (A), mid (B), and late (C) planted sorghum genotypes.

Early planted sorghum received 407.09 – 418.05 mm, optimal planting received 389.32 – 401.25 mm while late planted sorghum received 266.63 – 267.13 mm of rainfall (Table 2). The rainfall ranges depict total rainfall as received by different genotypes due to variations in time to physiological maturity. For all planting dates, recorded rainfall was less than sorghum water requirement. The observed onset of rainfall (November) occurred later relative to suggestions by historical data (September). This highlighted climate variability and vulnerability of rainfed agriculture in the region. In this regard, climate forecasts rather than historical data should be recommended to formulate planting dates to synchronize rainfall with growing period. Use of DAFF (2010) guidelines could be misleading as they lack sensitivity to rainfall variability between seasons and assume homogeneity of bio–resource groups (BRGs). The use of crop models is advantageous in forecasting planting dates across BRGs in SSA, however availability of soil and climate data for all BRGs remains a challenge to this effect.

Table 2: Water use efficiency (WUE) and water use characteristics at physiological maturity, and seed mass at harvest of four sorghum genotypes across three planting dates.

Planting date	Genotype	Rainfall received	Water use	Total yield	Panicle yield	Total WUE	Panicle WUE	Harvest index	1000 seed mass
		(mm)		($kg\ ha^{-1}$)		($kg\ ha^{-1}\ mm^{-1}$)			(g)
Early	PAN8816	407.09	390.5	9933.33[a]	4822.22[a]	25.437[a]	12.349[a]	0.485[a]	42.47[g]
	Macia	418.05	395.9	10613.33[a]	5791.11[ab]	26.808[a]	14.628[ab]	0.546[ab]	35.13[e]
	Ujiba	418.05	395.9	8884.44[a]	3688.89[bc]	22.441[a]	9.318[bc]	0.415[bc]	31.13[d]
	IsiZulu	418.05	395.9	10400.00[a]	2915.56[c]	26.269[a]	7.364[c]	0.280[c]	29.07[c]
Mean		**415.31**	**394.55**	**9957.78**	**4304.44**	**25.239**	**10.915**	**0.432**	**34.45**
Optimal	PAN8816	389.32	364.46	8946.67[a]	4524.44[a]	24.548[a]	12.414[a]	0.506[a]	38.07[f]
	Macia	401.25	389.56	12031.11[a]	6160.00[a]	30.884[a]	15.813[a]	0.512[a]	35.33[e]
	Ujiba	389.32	364.46	9008.89[ab]	3773.33[a]	24.718[ab]	10.353[a]	0.419[a]	28.20[bc]
	IsiZulu	393.12	364.66	15262.22[b]	3697.78[b]	41.853[b]	10.140[b]	0.242[b]	28.13[bc]
Mean		**393.25**	**370.79**	**11312.22**	**4538.89**	**30.501**	**12.180**	**0.420**	**34.43**
Late	PAN8816	266.63	237.61	4533.33[a]	2462.22[a]	19.079[a]	10.362[a]	0.543[a]	31.27[d]
	Macia	266.88	237.86	5746.67[a]	2960.00[a]	24.185[a]	12.457[a]	0.515[a]	26.83[ab]
	Ujiba	266.63	237.61	6293.33[a]	3173.33[a]	26.486[a]	13.355[a]	0.504[a]	25.40[a]
	IsiZulu	266.63	237.61	5417.78[a]	2613.33[a]	22.801[a]	10.998[a]	0.482[a]	26.17[a]
Mean		**266.69**	**237.61**	**5497.78**	**2802.22**	**23.138**	**11.794**	**0.511**	**27.42**
	LSD			185.29	79.47	2.834	0.977	0.028	1.92
	%CV			12.5	12.1	8.7	6.9	7.4	3.6

[a] Values sharing similar alphabets represent statistically yields and water use characteristics, whilst different alphabets represent significant different yields and water use characteristics across interaction of planting dates and genotypes.

Table 3: Rainfall received at three key developmental stages when planted at three planting dates.

Planting dates	Rainfall (mm) received during each growth stage			Total
	Initial	Development	Mid–season	
Early	79.47	151.11	187.43	418.05
Optimal	78.71	173.20	174.46	401.25
Late	204.19	40.86	22.08	267.13
‡Crop co–efficient (Kc)	0.45	0.83	1.18	2.46

‡Obtained from Shenkut *et al*. (2013).

Combining the seasonal rainfall prediction with crop water requirement and soil water information is the core component to successful agriculture. Sorghum water requirement ranges from 450–650 mm (Hensley et al., 2000; Jewitt et al., 2009) for optimal yield, assuming a growing season of 120–130 days. Even under sub–optimal seasonal rainfall, effective crop water use is attained when rainfall distribution between stages is proportionate with crop coefficient (K_c) for water requirements. The synergy between rainfall received per growth stage and K_c was least proportionate (Table 3) for late planted sorghum, where the least rainfall received was during mid–season stage when crop water requirements are maximum and most rain fell during initiation stage when crop water requirements are low. On the contrary, early planted sorghum received rainfall proportionate to K_c at different growth stages.

Final Emergence and Crop Establishment

The interaction between planting date and genotype was highly significant ($P<0.001$) with respect to final emergence (Table 4; Figure 3). Full emergence (100%) was achieved for all genotypes when sorghum was planted late. Consequently, crop establishment was fastest for the late planting date. Early establishment and high seedling emergence for all genotypes for late planted sorghum were attributed to high cumulative rainfall 7 days after sowing and high initial soil water content at sowing. At least 25 mm of rainfall should fall within a 7 day period after sowing (Raes et al., 2004; Mhizha et al., 2014) for early and optimal emergence. Final emergence was significantly low for Macia (57.6%), whilst other genotypes attained full establishment in response to early planting. Low initial SWC at sowing (Figure 2) resulted in delayed crop establishment for early planted sorghum for all genotypes compared to optimal and late planting dates. For all three planting dates, PAN8816 achieved full emergence, although there were variations in times to emergence. This was attributed to high seedling vigour in hybrids compared to landraces and OPVs. Emergence was shown to be significantly (P<0.001) slower and lower for the optimal planting date (Table 4); this trend was clearer for Macia (31.2% emergence 21 DAS) relative to other sorghum genotypes (Figure 3).

Table 4: Time taken for four sorghum genotypes planted at three different planting dates to reach a particular phenological stage.

Stage	Planting date	Time taken to reach phenological stage in days (growing degree days)					LSD	%cv
		Ujiba	Macia	PAN8816	IsiZulu	Mean		
CE	Early	21 (257.1)[c]	21 (257.1)[c]	14 (173.6)[b]	14 (173.6)[b]	17.5	1.98	2.1
	Optimal	28 (357.1)[d]	21 (257.9)[c]	14 (176.1)[a]	28 (357.1)[d]	22.2		
	Late	7 (107)[a]	14 (215.9)[b]	7 (107)[a]	7 (107)[a]	8.8		
EJ	Early	91 (1246.0)[e]	91 (1246.0)[e]	77 (1048.1)[c]	91 (1246.0)[e]	87.5	1.98	0.4
	Optimal	84 (1190.1)[d]	91 (1298.1)[e]	77 (1081.0)[c]	91 (1298.1)[e]	82.3		
	Late	63 (933.7) [a]	70 (1025.3)[b]	63 (933.7)[a]	63 (933.7)[a]	67.7		
FI	Early	98 (1355.2)[b]	98 (1355.2)[b]	84 (1158.9)[a]	98 (1355.2)[b]	94.5	2.03	0.6
	Optimal	91 (1298.1)[b]	98 (1390.3)[c]	84 (1190.1)[a]	98 (1390.3)[c]	92.8		
	Late	70 (1025.3)[a]	77 (1104.4)[b]	70 (1025.3)[a]	70 (1025.3)[a]	75.3		
F	Early	105 (1463.1)[e]	105 (1463.1)[e]	91 (1246.3)[e]	105 (1463.1)[e]	101.5	1.98	0.3
	Optimal	98 (1390.3)[d]	105 (1483.2)[c]	91 (1298.1)[c]	105 (1483.2)[c]	99.8		
	Late	84 (1170.3)[b]	84 (1170.3)[b]	77 (1104.4)[a]	84 (1170.3)[b]	82.3		
FD	Early	7 (92.4)[a]	7 (92.4)[a]	7 (108.9)[a]	7 (92.4)[a]	7	–	–
	Optimal	7 (92.9)[a]	7 (101.2)[a]	7 (92.2)[a]	7 (101.2)[a]	7		
	Late	7 (85.3)[a]	7 (85.3)[a]	7 (65.9)[a]	7 (85.3)[a]	7		
A	Early	112 (1555.4)[b]	112 (1555.4)[b]	98 (1355.2)[b]	112 (1555.5)[b]	108.5	2.00	0.6
	Optimal	105 (1483.2)[b]	112 (1584.4)[b]	98 (1390.3)[b]	112 (1584.4)[b]	106.8		
	Late	91 (1256.2)[b]	91 (1256.2)[b]	84 (1170.3)[a]	91 (1256.2)[b]	89.3		
GF	Early	119 (1648.2)[b]	119 (1648.2)[b]	105 (1463.1)[a]	119 (1648.2)[b]	115.5	1.98	0.6
	Optimal	112 (1584.4)[b]	119 (1703.6)[c]	105 (1483.2)[a]	119 (1703.6)[c]	113.8		
	Late	98 (1351.2)[b]	98 (1351.2)[b]	91 (1256.2)[a]	98 (1351.2)[b]	96.3		
PM	Early	140 (1976.3)[b]	140 (1976.3)[b]	133 (1868.6)[a]	140 (1976.3)[b]	138.3	1.76	0.4
	Optimal	126 (1811.2)[a]	140 (1999.5)[c]	126 (1811.2)[a]	133 (1907.9)[b]	131.3		
	Late	126 (1697.9)[a]	133 (1756.5)[c]	126 (1697.9)[a]	126 (1697.9)[b]	127.8		

CE (crop establishment); EJ (end of juvenile); FI (floral initiation); F (flowering); FD (flowering duration); A (anthesis); GF (start of grain filling); PM (physiological maturity).
[a] Values sharing similar alphabets represent statistically yields and water use characteristics, whilst different alphabets represent significant different yields and water use characteristics at each planting date.

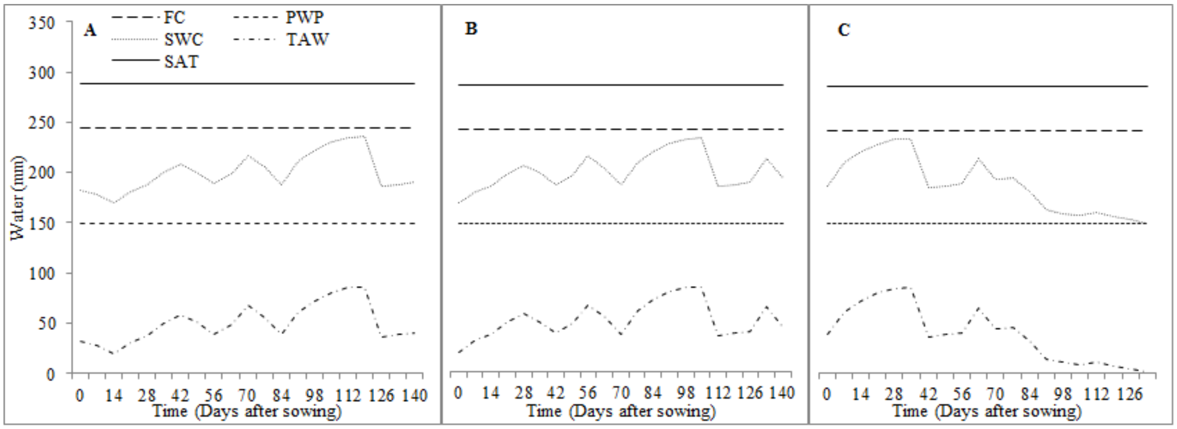

Figure 2: Soil hydraulic properties over time during the growing seasons of early, optimal, and late planted sorghum. Note: FC = Field capacity; PWP = Permanent wilting point; SWC = Soil water content; TAW = total available water; SAT = saturation point.

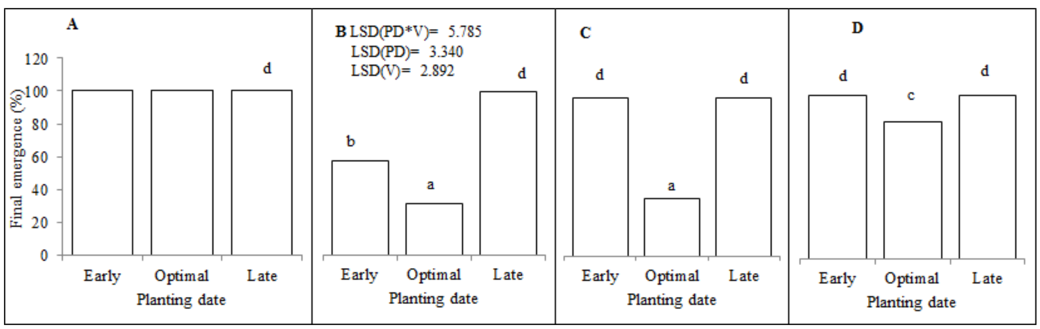

Figure 3: Final percentage emergence of sorghum genotypes (A) PAN8816, (B) Macia, (C) Ujiba, and (D) IsiZulu] planted at Ukulinga on three planting dates. Note: PD*V refers to the interaction between planting dates (PD) and sorghum genotypes (V), respectively. Values sharing the same letter are similar at LSD (PD*V) = 0.05.

Crop Morphology and Physiology

Late planted sorghum genotypes exhibited low ($P<0.001$) leaf number, CCI and SC (5.8; 47.22; 273.3 $mmol.m^{-2}.s^{-1}$) compared to early (7.7; 50.57; 298.7 $mmol.m^{-2}.s^{-1}$) and optimal (7.3; 51.74; 323.0 $mmol.m^{-2}.s^{-1}$) planting respectively. This was due to low SWC and TAW experienced during the late planting date (Saddam et al., 2014). This was more pronounced post floral initiation due to low and irregular rainfall during mid–season stage. Leaf number and CCI were statistically similar between early and optimal planting dates (Figure 4). This was attributed to similarities in climate due to closeness between the two planting dates, which highlights the need to use area specific climate forecasting instead of historical data and countrywide recommendations for planting date selections. Sorghum genotypes maintained statistically similar ($P>0.05$) CCI (Figure 7) and stomatal conductance (Figure 8) across planting dates. However, leaf number varied significantly among genotypes (P<0.001; Figure 4). Highest leaf number was observed for PAN8816 (7.4) followed by Macia (7.2). Leaf numbers were lowest and statistically similar for IsiZulu (6.6) and Ujiba (6.5) landraces. Leaf number variations across genotypes were attributed to genotypic differences. Chlorophyll content index increased and plateaued after floral initiation with peak CCI measurements ranging between 50 and 61; these results were similar to observations by van Oosterom et al. (2010). Stomatal conductance in landraces was less sensitive to differences in TAW compared to the OPV and hybrid genotypes. Results of leaf number, CCI and SC suggested that sorghum was subjected to significant water stress, especially when planted late. This was consistent with observations of soil water content (Figure 2) and rainfall (Table 2) across the different sites which showed that soil water availability and rainfall were limiting during the late planting date.

Growth indicators of plant height and leaf number increased gradually until flowering and end of vegetative stage, respectively. Increase in plant height in sorghum occurred mostly during the vegetative stage, and full panicle formation coincided with attainment of maximum plant height (Figure 5). Planting dates and varietal differences significantly (P<0.05) affected plant height. Late planted sorghum grew tallest for all genotypes, albeit with fewer leaves relative to the other planting dates. An exception was IsiZulu landrace, where plant height reduced at late planting resulting in decreased biomass and marked improved HI. Longer but thinner shoots were associated with a lower biomass accumulation under severe water stress for the late planting date. This suggests that plant height, stem diameter and leaf number form key adaptations of shoot growth to water stress in sorghum.

Canopy cover largely relies on crop density and plant leaf material. Increases in CC limit water loss from soil by evaporation, whilst improving water portion allocated to crop biomass production via transpiration (Mabhaudhi et al., 2013). Variations in measured CC were significant for both planting dates (P<0.001) and genotypes (P<0.05). Canopy cover for the early planted crop benefitted from good crop stand and high leaf number. Low CC for the late planted crop was associated with low leaf number. Canopy cover was lowest at optimal planting date due to low crop stand. Decreased crop stand in landrace and OPV genotypes and delayed emergence contributed mostly to observed low CC (Figure 7). It may also be that, the low canopy cover at the late planting date allowed for more soil evaporation to occur. This may have inadvertently worsened the situation of low SWC and TAW as less soil water was available for productive water loss (transpiration).

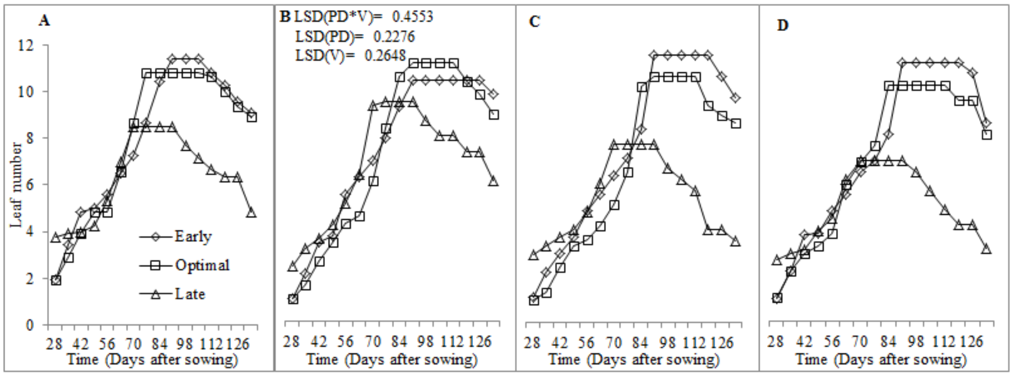

Figure 4: Leaf number progressions observed after establishment in PAN8816 (A), Macia (B), Ujiba (C) and IsiZulu (D) sorghum genotypes planted on different planting dates. Note: PD*V refers to the interaction between planting dates (PD) and sorghum genotypes (V), respectively.

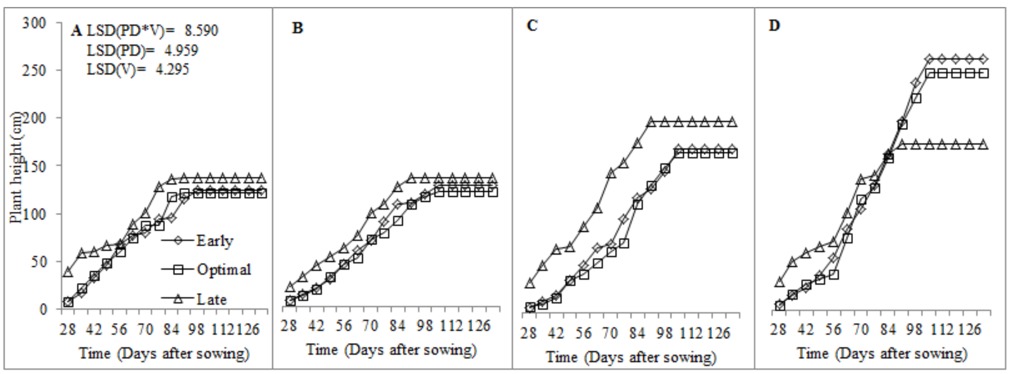

Figure 5: Plant height observed after establishment in PAN8816 (A), Macia (B), Ujiba (C) and IsiZulu (D) sorghum genotypes planted on different planting dates. Note: PD*V refers to the interaction between planting dates (PD) and sorghum genotypes (V), respectively.

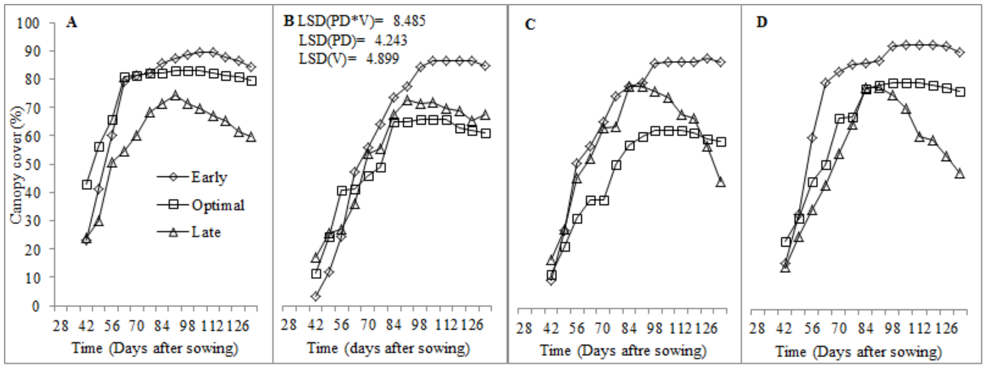

Figure 6: Percent canopy cover in PAN8816 (A), Macia (B), Ujiba (C) and IsiZulu (D) sorghum genotypes planted on different planting dates. Note: PD*V refers to the interaction between planting dates (PD) and sorghum genotypes (V), respectively.

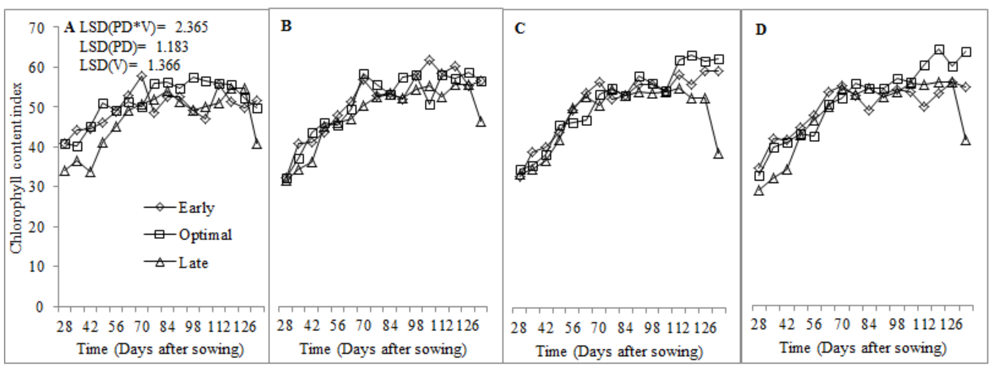

Figure 7: Chlorophyll content index in PAN8816 (A), Macia (B), Ujiba (C) and IsiZulu (D) sorghum genotypes planted on different planting dates from establishment until maturity. Note: PD*V refers to the interaction between planting dates (PD) and sorghum genotypes (V), respectively.

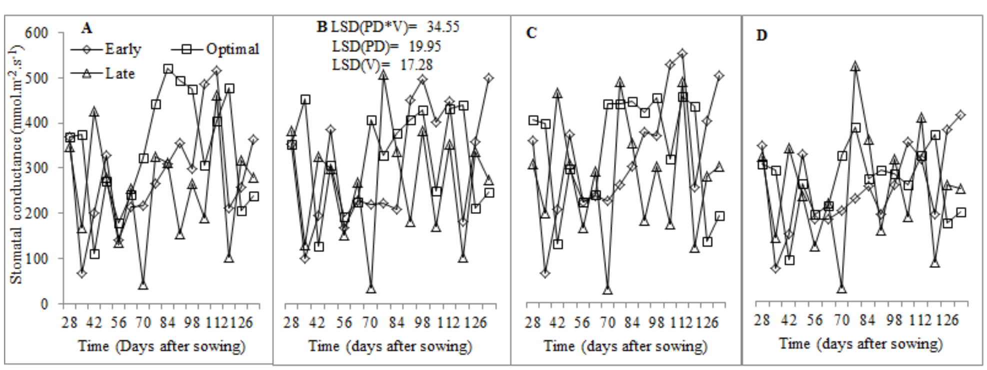

Figure 8: Stomatal conductance in PAN8816 (A), Macia (B), Ujiba (C) and IsiZulu (D) sorghum genotypes planted on different planting dates from establishment until maturity. Note: PD*V refers to the interaction between planting dates (PD) and sorghum genotypes (V), respectively.

Phenological Development and Yield

Early planting generally resulted in delayed phenological development and maturity, resulting in a longer (Table 4) but slower grain filling duration as depicted by harvest index accumulation. Hybrid and landrace genotypes had a significantly ($P<0.05$) shorter growing season relative to the OPV for all planting dates. It could be argued that Macia employs quiescence strategies to a greater degree relative to the hybrid and landrace genotypes to adapt to irregular rainfall and water scarcity, hence delays in time to physiological maturity. Genotypes that employ quiescence are expected to delay rather than hasten physiological maturity under severe water stress, and low, irregular rainfall. However, observed shortening of growing cycle for late planting date under severe water stress for the late planting date suggests that Macia is a late maturing genotype. Which explains consistently longer growing cycle in Macia compared to the hybrid and landrace genotypes. Phenological development hastened for all genotypes under late planting in order to escape both pre– and post–anthesis water stress. This resulted in early flowering, decreased panicle mass and total biomass at late planting. Water stress potentially resulted in decreased head size at floral initiation, flower abortion at flowering, and few assimilates for grain filling. This resulted in reduced seed mass and panicle yield in late planted sorghum (Table 2). Early planted sorghum had significantly ($P<0.001$) higher seed mass (34.5 g) compared to optimal (32.4 g) and late (27.4). Seed mass was linked to water availability at mid–season stage (Table 3), which directly affected photosynthesis and yield accumulation at grain filling stage.

Tall growing genotypes consistently had high dry biomass accumulation (Figure 9) and, in comparison, small source to sink biomass partitioning (Figure 10), resulting in lower harvest index (Figure 11). In general, build–up of harvest index (Figure 11) and final harvest index (Table 2) improved with decreasing rainfall, reinforcing sorghum as an exemplar drought–tolerant cereal for production in arid and semi–arid regions. The improvement in HI under stress highlights that water stress has a positive effect on HI of sorghum. This implies that, when subjected to stress, the crop will partition more of its assimilates to the yield component which is a desirable characteristic under rainfed conditions. The isiZulu landrace decreased shoot (plant height) growth to increase source to sink biomass partitioning under severe water stress at late planting. This resulted in two–fold increases in HI, highlighting high adaptation of the landrace to low and irregular rainfall. At early and optimal planting, highest panicle yield (Figure 10) and harvest index (Figure 11) were observed in Macia, due to extended grain filling period and late maturity. This shows adaptation of Macia OPV to sub–optimal rainfall regions and the benefit of deliberate breeding for drought tolerance in sorghum. However, late planting significantly reduced Macia yield by more than two–fold implying that further breeding for severe water stress and periodic rainfall need to be conducted for OPVs. Low sorghum biomass and panicle yields at late planting were attributed to low leaf number, CCI, SC and CC in response to low and disproportionate rainfall. This was exacerbated by flowering coinciding with declining rainfall and temperatures as winter set in. Comparison between expected time to maturity were done using days to maturity instead of thermal time, as this is how genotypes are described by seed manufacturers. PAN8816 matured within (126–133 DAS) expected time since it is medium–late maturing genotype (120–130). Compared to expected time to flowering (60–65 DAS) and maturity (115–120 DAS), Macia flowering (77–84 DAS) and physiological maturity (133–140 DAS) was delayed. A more accurate comparison between expected and observed phenological development would have been the use of thermal time, as this method accounts for temperature differences between agro–ecologies.

Landraces showed panicle yield stability across planting dates, whilst the OPV and hybrid genotypes had significantly less panicle yield in response to decreased water availability and erratic rainfall distribution at late planting. This suggests that landraces have greater environmental plasticity compared to the OPV and hybrid. Ujiba and IsiZulu landraces therefore have yield advantages under sever water stress and uneven rainfall distribution; however, at relatively low water stress, the hybrid and OPV genotypes confer a yield advantage. Continued landrace cultivation in semi–arid, rainfed conditions by small–scale farmers makes landraces particularly suited for production under low rainfall areas, and a valuable germplasm resource in breeding for drought tolerance.

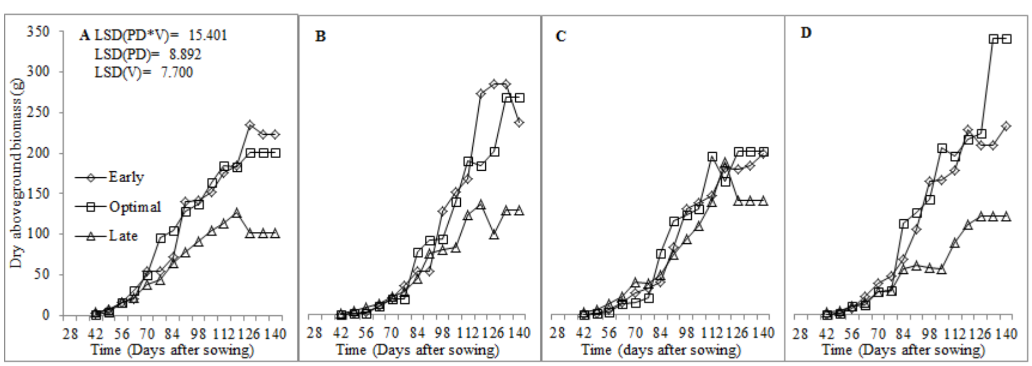

Figure 9: Destructively sampled dry aboveground biomass of PAN8816 (A), Macia (B), Ujiba (C) and IsiZulu (D) sorghum genotypes planted on three different planting dates. Note: PD*V refers to the interaction between planting dates (PD) and sorghum genotypes (V), respectively.

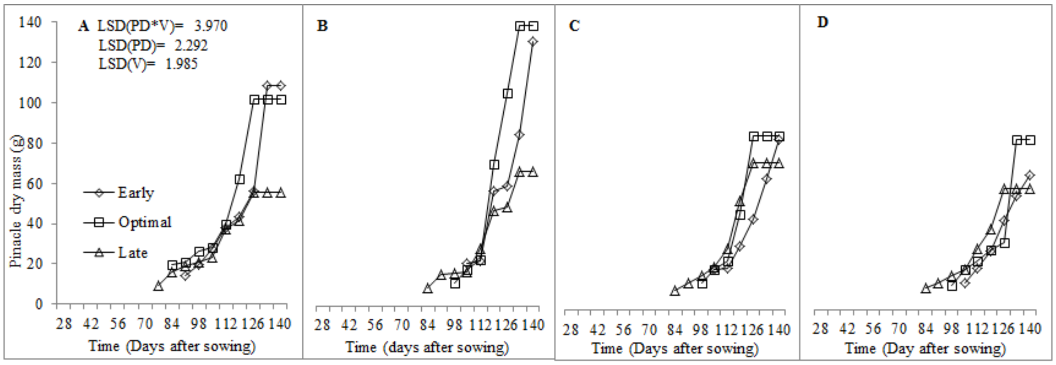

Figure 10: Destructively sampled pinnacle mass of PAN8816 (A), Macia (B), Ujiba (C) and IsiZulu (D) sorghum genotypes planted on three different planting dates. Note: PD*V refers to the interaction between planting dates (PD) and sorghum genotypes (V), respectively.

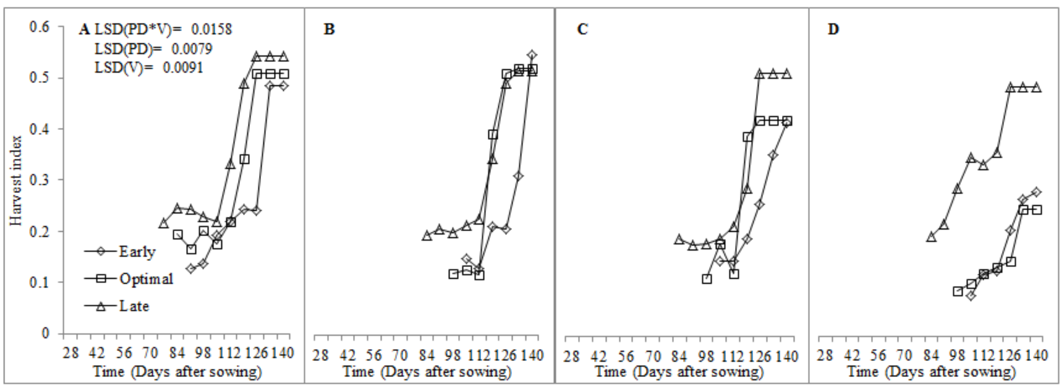

Figure 11: Build–up of harvest indices in PAN8816 (A), Macia (B), Ujiba (C) and IsiZulu (D) sorghum genotypes planted on three different planting dates. Note: PD*V refers to the interaction between planting dates (PD) and sorghum genotypes (V), respectively.

Water Use and WUE

Water use was sub–optimal for all planting dates; this was associated with below average rainfall received. Measured crop water use was exceptionally low, confirming severe water stress experienced by genotypes for the late planting date. The interaction of planting dates and genotypes was significant ($P<0.001$) for biomass and yield WUE. Biomass and yield WUE were highest at optimal planting (30.5 and 12.2 kg ha^{-1} mm^{-1}), relative to late (23.1 and 11.8 kg ha^{-1} mm^{-1}), and early planting dates (25.2 and 10.9 kg ha^{-1} mm^{-1}). For the hybrid and OPV, biomass and yield WUE decreased in response to low TAW, and irregular and disproportionate rainfall experienced during the late planting date. By contrast, biomass and yield WUE for the landraces improved with decreasing rainfall (Table 2). This reinforces findings in this study that landraces are highly suitable for production under severe water stress, as more 'food per drop' is produced with less rainfall.

CONCLUSIONS

Rainfall received for all planting dates was sub–optimal. Rainfall for the late planting was relatively low, highly irregular and disproportionate to crop water requirements at key growth stages. Low TAW at planting was associated with delayed crop establishment and low final emergence. The exception was PAN8816 hybrid were full emergence was achieved for all planting dates. Genotypes adapted to low and irregular rainfall by decreasing CC, CCI and SC, and hastened phenological development. This resulted in low biomass and yield for late planted sorghum. Landraces showed panicle yield stability across planting dates, whilst the OPV and hybrid genotypes had significantly lower panicle yield under low soil water availability and uneven rainfall distribution experience for the late planting date. Biomass and yield WUE were highest for the optimal planting date relative to the late and lowest at early planting dates. Hybrid and OPV biomass and yield WUE decreased in response to low TAW, and irregular and disproportionate rainfall at late planting. Whereas biomass and yield WUE in landraces improved with decreasing rainfall. This suggests that hybrid genotypes can be cropped to increase crop stand under low soil water availability, OPVs can be cropped at optimal planting to benefit from high yield and HI, whereas landraces are a valuable germplasm resources under severe low rainfall conditions. Breeding for improved seedling vigour, yield, HI and low tannins in landrace genotypes can potentially assist farmers improve yield quality and quantity under high rainfall conditions, whilst benefiting from relatively high drought tolerance under low and irregular rainfall. Delayed onset of rainfall and high variability in rainfall during the growing seasons suggests that use of climate forecast in place of historical data recommended be used in selecting planting dates. In this regard, crop models can be useful. This study was only presented with data from a single site and year, and further data needs to be collected to verify the results observed in this study.

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CHAPTER 5

CALIBRATION AND TESTING OF AQUACROP FOR SELECTED SORGHUM GENOTYPES

Sandile T. Hadebe, Tafadzwanashe Mabhaudhi, Albert T. Modi

S.T. Hadebe, T. Mabhaudhi, and A.T. Modi, Department of Crop Science, School of Agricultural Earth and Environmental Sciences, Univ. of KwaZulu-Natal, Pietermaritzburg, South Africa *Corresponding author (hadebesta@gmail.com).

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Abstract

Predicting yield response to water is important in rainfed agriculture. The objective of this study was to calibrate and test AquaCrop for three sorghum genotypes (PAN8816, a hybrid; Macia, an open–pollinated variety; and Ujiba, a landrace) during 2013/14 and 2014/15 planting seasons (early, optimal and late planting dates). Variables considered during model evaluation included canopy cover (CC), biomass (B) and yield (Y). The model was able to simulate CC ($R^2 \geq 0.710$; RMSE ≤ 22.73%; d ≥ 0.998), biomass accumulation ($R^2 \geq 0.900$; RMSE≤ 10.45%; d≥ 0.850), harvest index ($R^2 \geq 0.902$; RMSE ≤ 7.17%; d ≥ 0.987) and yield ($R^2 \geq 0.945$; RMSE ≤ 3.53%; d ≥ 0.783) well for all genotypes and planting dates. AquaCrop overestimated biomass and crop yield. This was attributed to default values used to describe canopy sensitivity to water stress and water stress coefficients. While these values provided satisfactory simulations, confirming model robustness, there is a need to develop genotype specific parameters to improve model goodness of fit. The model confirmed sorghum drought tolerance and its viability for production under water limited conditions. The relatively good simulations produced by the ten step calibration confirm AquaCrop's simplicity and suitability for use in places where extensive data sets may be unavailable.Biomass and yield overestimation resulting from the use of the ten step calibration procedure suggests that other parameters (canopy sensitivity to water stress and water stress coefficient) are required to improve canopy and yield predictions for sorghum genotypes.

Keywords: modelling, parameterization, sorghum, water availability.

Introduction

High seasonal rainfall variability, delays in onset and irregular distribution of rainfall, and occasional dry spells within seasons negatively impact cereal yields and household livelihoods in sub–Saharan Africa (SSA) (Fjelde & von Uexkull, 2012). The impact is exacerbated under rainfed agriculture, where rainfall is the sole water input into the agriculture system. Variability in rainfall affects timing and location of planting, as onset, cessation and amount of rainfall affect farmers' planting decisions. Cereal crops are a major contributor to food security and economy in arid and semi–arid regions. In SSA, a region where 95% of agriculture is rainfed (Singh, Wani, Pathak, Sahrawat, & Singh, 2011), and arid and semi–arid areas account for 43% of total area (Food and Agriculture Organization [FAO], 2008), rainfall is a major limitation to cereal yields. Sorghum is predominantly grown in semi–arid and arid agro–ecologies of SSA, under rainfed conditions. This makes sorghum production highly susceptible to rainfall amount and distribution.

Examining yield response to rainfall amount and distribution under rainfed environments is both laborious and expensive. In consideration of such limitations, the use of crop models is useful. Crop models are valuable prediction tools where environments, soils, genotypes and climatic conditions vary. For increased accuracy of model predictions, models have to be parameterized, calibrated and tested before use. For model calibration, one changes model parameters and even coding in order to obtain accurate prediction versus observed data. On the other hand, testing is the process whereby the model is run against independent data, without any modification of model parameters or code. AquaCrop is a crop water productivity model developed by the Land and Water Division of FAO that simulates crop yield response to water (Raes, Steduto, Hsiao, & Fereres, 2009b; Steduto, Hsiao, Raes, & Fereres, 2009). AquaCrop predicts crop productivity, water requirement, and water use efficiency and is particularly suited to address conditions where water is a key limiting factor in crop production.

Genotypic and environmental differences impact sorghum adaptation and ultimately yield and water use (Karunaratne et al., 2011). AquaCrop has been parameterized and tested for a wide range of crops (Farahani, Izzi, & Oweis, 2009; Geerts et al., 2009; Hsiao et al 2009; Karunaratne et al., 2011; Steduto et al., 2009) under different environmental conditions illustrating that the model could accurately simulate yield response to water. AquaCrop has already been parameterized for sorghum. However, there is a need to perform a local calibration for sorghum genotypes under production in SSA. This study aimed to calibrate and test AquaCrop for hybrid, open–pollinated and landrace sorghum genotypes. A major selling point of AquaCrop is its simplicity, the ability to use minimal inputs during calibration to produce reliable estimates of crop yield response to water under testing scenarios. In this study, a ten step calibration procedure was used to calibrate sorghum genotypes, and subsequently test model performance under variable climatic conditions. In part, this study aimed to investigate whether minimal calibration (ten step calibration procedure) proposed for non–research AqauCrop users was sufficient in predictions of sorghum yield response to water. The choice of genotypes used is explained in the materials and methods section.

Materials and Methods

Model Description

The Food and Agriculture Organization's (FAO) AquaCrop crop model is a water-driven simulation model (generic crop water productivity model) (Steduto et al., 2009; Raes et al., 2009).

It requires a relatively low number of parameters and input data to simulate yield response to water of most major field and vegetable crops. Its parameters are explicit and mostly intuitive and the model maintains sufficient balance between accuracy, simplicity and robustness (Steduto et al., 2009; Raes et al., 2009).

The particular features that distinguish AquaCrop from other crop models is its focus on water, the use of ground canopy cover instead of leaf area index, and the use of water productivity values normalized for climate (atmospheric evaporative demand and of carbon dioxide concentration). This confers the model an extended extrapolation capacity to diverse locations and seasons (Steduto et al., 2007), including future climate scenarios. The model uses canopy ground cover (CC) instead of leaf area index (LAI) as the basis to calculate transpiration and to separate soil evaporation from transpiration. Biomass is then calculated as the product of transpiration and a water productivity parameter (Equation 1).

$$\mathbf{B = WP\ x \sum Tr} \qquad \text{Equation 1}$$

where: B = aboveground biomass (ton/ha),

WP = water productivity (biomass per unit of cumulative transpiration), and

Tr = crop transpiration.

Crop yield is then calculated as the product of above-ground dry biomass and harvest index (HI):

$$\mathbf{Y = B\ x\ HI} \qquad \text{Equation 2}$$

where: Y = crop yield,

HI = harvest index.

Although the model is simple, it gives particular attention to the fundamental processes involved in crop productivity and in the responses to water, from a physiological and agronomic perspective (Raes et al., 2009). The FAO AquaCrop model predicts crop productivity, water requirement, and water use efficiency under water-limiting conditions (Raes et al., 2009). AquaCrop considers the soil, with its water balance; the plant, with its development, growth and yield processes; and the atmosphere, with its thermal regime, rainfall, evaporative demand and carbon dioxide concentration. In this study, user defined model inputs were used to describe soil physical and hydraulic properties, daily weather, and 10 user–specific crop parameters for each sorghum genotype obtained from field trials. Additionally, the model also considers some management aspects such as irrigation and fertility, as they affect the soil water balance, crop development and therefore final yield. Pests, diseases, and weeds are not considered (Raes et al., 2009a).

Plant material

Three sorghum genotypes, a hybrid (PAN8816), an open-pollinated variety (Macia) and a landrace (Ujiba), were selected for this study. This reflected the range of germplasm typically used by farmers for sorghum production in southern Africa. The hybrid PAN8816, represented the preferred seed source by commercial sorghum farmers. PAN8816 was sourced from Pannar Seeds®. Macia is a popular low tannin, open-pollinated variety developed by the International Crop Research Institute for the Semi–Arid Tropics (ICRISAT), under production in most sorghum growing regions across SSA (Takele and Farrant, 2013; Charyulu et al., 2015 Ujiba is a high tannin landrace representing a popular seed choice among subsistence farmers in rural KwaZulu Natal, South Africa. It was sourced locally from smallholder farmers in Tugela Ferry, South Africa (28°44'S, 30°27'E).

Site description

Field trials were planted at Ukulinga Research Farm (30°24'S, 29°24'E, 805 m a.s.l) on 03 November 2014, 17 November 2014, and 26 January 2015. The farm is situated in Pietermaritzburg in the subtropical hinterland of KwaZulu-Natal province. Ukulinga represents a semi-arid environment and is characterized by clay-loam soils (USDA taxonomic system). Rain falls mostly in summer, between September and April. Rainfall distribution varies during the growing season (Swemmer et al., 2007) with the bulk of rain falling in November, December and early January. Occasionally light to moderate frost occurs in winter (May – July).

Trial layout and design

Field trials planted at Ukulinga on 17 January during the 2013/14 were used to parameterize each of the three sorghum genotypes. The experimental design used was a randomized complete block design with three replications. Independent field trials planted in the 2014/15 season were used to test model performance. The experimental design was a split–plot design with planting date as the main factor and genotypes as the sub–factor laid out in randomised complete blocks with three replications. The planting (03 November 2014, 17 November 2014, and 26 January 2015) represented early, optimal and late planting dates for sorghum. Early planting reflected onset of rainfall at Ukulinga in 2014/15 season. Optimal planting date was based on DAFF (2010) recommendations and historical weather data at Ukulinga. Late planting date represented latest planting from which seasonal rainfall can sustain 120–140 day growing season (Table 2). All trials comprised three sorghum cultivars, namely: PAN8816, Macia and Ujiba. The trials measured 310 m^2, with individual plot size of 6 m * 4.5 m (18 m^2), with 1 m interplot spacing between the plots. Final inter-row spacing was 0.75 m with 0.30 m intra-row spacing, amounting to 21 plants per row and 63 experimental plants per plot. Each individual plot had seven rows with the three inner most rows as the experimental plants, and the remaining rows reserved for destructive sampling. Planting rows were dug ≈25 mm deep, seeds were sown closely and thinned to the desired crop density after establishment.

Table 7: Experiments at Ukulinga experimental site used to develop model parameters to calibrate and test AquaCrop.

Purpose	Experiments	Planting date
Parameterization	Rainfed	17 January 2014
	Early planting date – rainfed	03 November 2014
Testing	Optimal planting date – rainfed	17 November 2014
	Late planting date – rainfed	26 January 2015

Agronomic practices

Soil samples were collected and analysed for fertility before land preparation. Before planting, fallow land was mechanically ploughed, disked and rotovated. A pre-emergence herbicide, Round-up® (glyphosate at 10 ml per litre of water) was applied to control weeds two weeks before planting. A deficit of fertilizer requirements (Smith, 2006) was applied using Gromor Accelerator® (30 g kg^{-1} N, 15 g kg^{-1} P and 15 g kg^{-1} K), a slow release organic fertilizer at 14 days after sowing (DAS). Planting rows were opened by hand 25 mm deep and seeds were hand-sown in the ground. Planting was conducted by drilling sorghum seeds. Thereafter, at crop establishment (14 DAS), seedlings were thinned to the required spacing. Scouting for pests and diseases was done weekly. Cypermethrin® (15 mℓ per 10 ℓ knapsack) was applied to control insect pests one month after planting. Weeding was done using hand-hoes at frequent intervals.

Input Data

Soil

Important soil input parameters required by AquaCrop model are: soil texture, volumetric water content at field capacity (FC), at permanent wilting point (PWP), and at saturation (SAT), saturated hydraulic conductivity (Ksat), and soil thickness (depth of soil profile) (Table 2). The soil textural class was described as clay (USDA Taxonomic System). Soil physical and hydraulic properties were obtained from classification and characterisation of experimental site soils by Mabhaudhi (2012). Soil hydraulic and physical properties were used to develop a soil (.SOL) file in the model.

Table 2: Soil characteristics from the experimental site at Ukulinga Research Farm.

Parameter	Texture	Thickness	PWP	FC	SAT	TAW	Ksat
		(m)	———(volume %)———			($mm.m^{-1}$)	($mm.d^{-1}$)
Value	Clay	0.6	28.3	40.6	48.1	123.0	25.0

Meteorological data

The climate file in AquaCrop is defined using maximum temperature (°C), minimum temperature (°C), rainfall (mm) and reference evapotranspiration (mm). Meteorological data for Ukulinga was obtained from an automatic weather station (within 100 m radius) courtesy of the Agricultural Research Council – Institute for Soil, Climate and Water (ARC–ISCW). Reference evapotranspiration was obtained from the weather station and was based on the FAO Penman-Monteith equation. Carbon dioxide concentration was obtained from AquaCrop's default Maunalua file. Meteorological data was used to develop the climate (CLI) file in the model.

Crop growth and development parameters

Ten crop parameters were used to calibrate AquaCrop's default sorghum file (Raes, Steduto, Hsiao, & Fereres, 2012) for the three sorghum genotypes as part of the ten step calibration procedure. The ten step procedure includes providing input data for the following: planting date, planting density, time to crop establishment, time to flowering, flowering duration, maximum canopy cover, time to maximum canopy cover, time to senescence, time to physiological maturity, and harvest index

(Table 3). The ten step procedure includes rooting depth. However, in this study, we used the default depth in the default sorghum file.

Date of planting was recorded as actual day when seeds were sown in the soil. Planting density was calculated as number of plants per given area based on row spacing and plant spacing. Area measurements were converted from m^2 to hectares and planting density was reported in plants/ ha. Time taken to reach phenological stages was recorded in days as when ≥50% of planting population exhibited diagnostic signs of that particular stage. Highest recorded canopy cover values from recorded data were taken as maximum canopy cover achieved by the crop for each genotype. To quantify effective rooting depth, an area around a plant root zone was dug out 1 m deep and 0.5 m from the main stem at physiological maturity. After which, the soil around the roots was brushed off, and root length was measured from exposed roots. The model is capable of simulating the presence of an impeding layer. Soil profiling at the experimental site revealed that the effective rooting depth of the soil was 0.6 m which was then input into the soil file. While for the crop it was maintained as the default 2 m. during model runs, root growth will be limited by the depth of the soil profile, while the value of 2 m represents the crop's potential in the absence of an impeding layer or a shallow soil. This feature allows then for the same crop file to be used for different soils without the need to change the crops' effective rooting depth whenever the soil file is changed.

Flowering was observed as time taken for 50% of experimental plant population to panicle bloom. Duration of flowering was recorded as time taken from flowering to when 50% of experimental population exhibited anthesis. Physiological maturity was observed when a dark spot appeared on the opposite side of the kernel from the embryo signaling completion of dry matter accumulation. However, physiological maturity in model simulations was observed as when dry matter accumulation (biomass and yield) ceased. Reference harvest index was calculated as the ratio of yield over total biomass at physiological maturity (Equation 2). Crop growth and development parameters were as inputs in genotype crop (.CRO) in the model.

Table 8: User–specific crop parameters used in parameterization of three sorghum genotypes (PAN8816, Ujiba and Macia) plus the original Aquacrop default sorghum crop file values.

Parameter	Genotype			
	PAN8816	**Ujiba**	**Macia**	**Default sorghum crop file**
Planting density (plants/ ha)	44 444	44 444	44 444	44 444
Time to crop establishment (days)	14	14	14	14
Maximum canopy cover (%)	89.1	80.3	80.3	89
Time to maximum canopy cover (%)	70	77	84	84
Time to flowering (days)	70	77	79	70
Duration of flowering (days)	14	14	14	27
Time to canopy senescence (days)	126	126	126	98
Time to physiological maturity (days)	140	140	140	140
Harvest index (%)	54	48	52	45

Model calibration

Field trials planted at Ukulinga on 17 January during the 2013/14 were used to calibrate each of the three sorghum genotypes. Simulations were performed with the AquaCrop model (Version 4.0) as described by Raes et al. (2009a) and Steduto et al. (2009). Key inputs in the model included: climate file, soil file, and crop file. Calibration of the model was conducted using 2013/14 data from rainfed trials conducted at Ukulinga. Initial calibration involved matching the observed to the simulated canopy cover, since AquaCrop is a canopy level model. Subsequent to this, the model was calibrated by comparing observed and simulated biomass, yield and harvest index. Data used for calibration were not used for testing.

Model testing

Testing is an important step of model verification. It involves a comparison between independent field measurements (data) and simulated output created by the model. Testing confirms whether or not results obtained from the model can be relied on and if they compare well with experimental obtained results. Model testing in this study was done by comparing canopy cover, biomass, yield and harvest index simulated by the model and those from the observed field experiments planted at different planting dates during the 2014/15 season (Table 1). Trials planted in the 2014/15 season were used to test the model.

Statistical analysis

Different statistical indices including coefficient of determination (R^2), root mean square error (RMSE) and its systematic ($RMSE_S$) and unsystematic components ($RMSE_U$) as well as the index of agreement (*d–index*) were used for comparison of simulated against observed data. Systematic RMSE was calculated (Loague et al., 1991) as follows:

$$\mathbf{RMSE} = \left[\frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I}(P_j^i - O_j^i)^2\right]^{0.5} \qquad \text{Equation 3}$$

where: n is the number of observations, P_i and O_i refer to simulated and observed values of the study variables, respectively. The RMSE is a good overall measure of model performance. It indicates the absolute fit of a model to observed field data, and evaluate closeness between the two values. The RMSE was normalized by expressing it as a percentage of data range to remove scale dependency. The simulation is considered excellent with a normalized RMSE is less than 10%, good if the normalized RMSE is greater than 10% and less than 20%, fair if normalized RMSE is greater than 20 and less than 30%, and poor if the normalized RMSE is greater than 30% (Jamieson et al., 1991).

Systematic Root Mean Square Error ($RMSE_S$) was calculated as the square root of the mean squared difference in regressed prediction-observation pairings within a given analysis region and for a given time period (Loague et al., 1991).

$$\mathbf{RMSE_s} = \left[\frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I}(\hat{P}_j^i - O_j^i)^2\right]^{0.5} \qquad \text{Equation 4}$$

where: P^i_j is the individual predicted quantity at site i and time j, P^ is the least square aggression, O^i_j is the individual quantity at site *i* and time *j*, and the summations are over all sites (*I*) and over time periods (*J*). And the least square aggression (P^) is:

$$\hat{P} = a + b\, O_j^i \qquad \text{Equation 5}$$

where: *a* is the y-intercept, and b is the slope of the resulting straight line fit.

The $RMSE_S$ estimates the model's linear (or systematic) error; hence, the better the regression between predictions and observations, the smaller the systematic error.

Unsystematic Root Mean Square Error ($RMSE_U$) was calculated as the square root of the mean squared difference in prediction-regressed prediction pairings within a given analysis region and for a given time period.

$$\mathbf{RMSE_U} = \left[\frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I}(P_j^i - \hat{P}_j^i)^2\right]^{0.5} \quad \text{Equation 6}$$

The unsystematic difference is a measure of how much of the discrepancy between estimates and observations is due to random processes or influences outside the legitimate range of the model.

The index of agreement (d–index) proposed by Willmott et al. (1985) was estimated (Equation 7). The d-index condenses all the differences between model estimates and observations within a given analysis region and for a given time period (hourly and daily) into one statistical quantity. It is the ratio of the total RMSE to the sum of two differences – between each prediction and the observed mean, and each observation and the observed mean. Viewed from another perspective, the index of agreement is a measure of the match between the departure of each prediction from the observed mean and the departure of each observation from the observed mean. Thus, the correspondence between predicted and observed values across the domain at a given time may be quantified in a single metric and displayed as a time series. The index of agreement has a theoretical range of 0 to 1. According to the d-index, the closer the index value is to one, the better the agreement between the two variables that are being compared and vice versa.

$$\boldsymbol{d} = \mathbf{1} - \left[\frac{\sum_{i=0}^{n}(P_i - O_i)^2}{\sum_{i=0}^{n}(|P_i| - |O_i|)^2}\right] \quad \text{Equation 7}$$

where: n is the number of observations, P_i the predicted observation, O_i is a measured observation, $IP_iI = P_i - M$ and $IO_iI = O_i - M$ (M is the mean of the observed variable). The simulated model results were compared statistically to observe experimental measurements using Microsoft Excel.

Results and Discussion

Calibration

AquaCrop is canopy level model (Mabhaudhi, Modi & Beletse, 2014). As such, the canopy through its expansion, ageing, conductance and senescence, is central to the model as it determines the amount of water transpired, which in turn determines the amount of biomass produced (Raes et al., 2009b). AquaCrop simulated canopy cover ($R^2 \geq 0.659$; RMSE $\leq$ 14.35%; d $\geq$ 0.999), biomass ($R^2 \geq 0.79$; RMSE $\leq$ 10.14%; d $\geq$ 0.908), harvest index ($R^2 \geq 0.967$; RMSE $\leq$ 3.55%; d $\geq$ 0.998) and yield ($R^2 \geq 0.923$; RMSE $\leq$ 3.82%; d $\geq$ 0.770) satisfactorily for all three genotypes during calibration (Figure 1). Root mean-square error was low, good goodness of fit (n = 16) and Willmot's *d*–index values were close to 1 implying that model predicted values were close to observed values. This gave confidence in calibration of the model and allowed model testing using independent data.

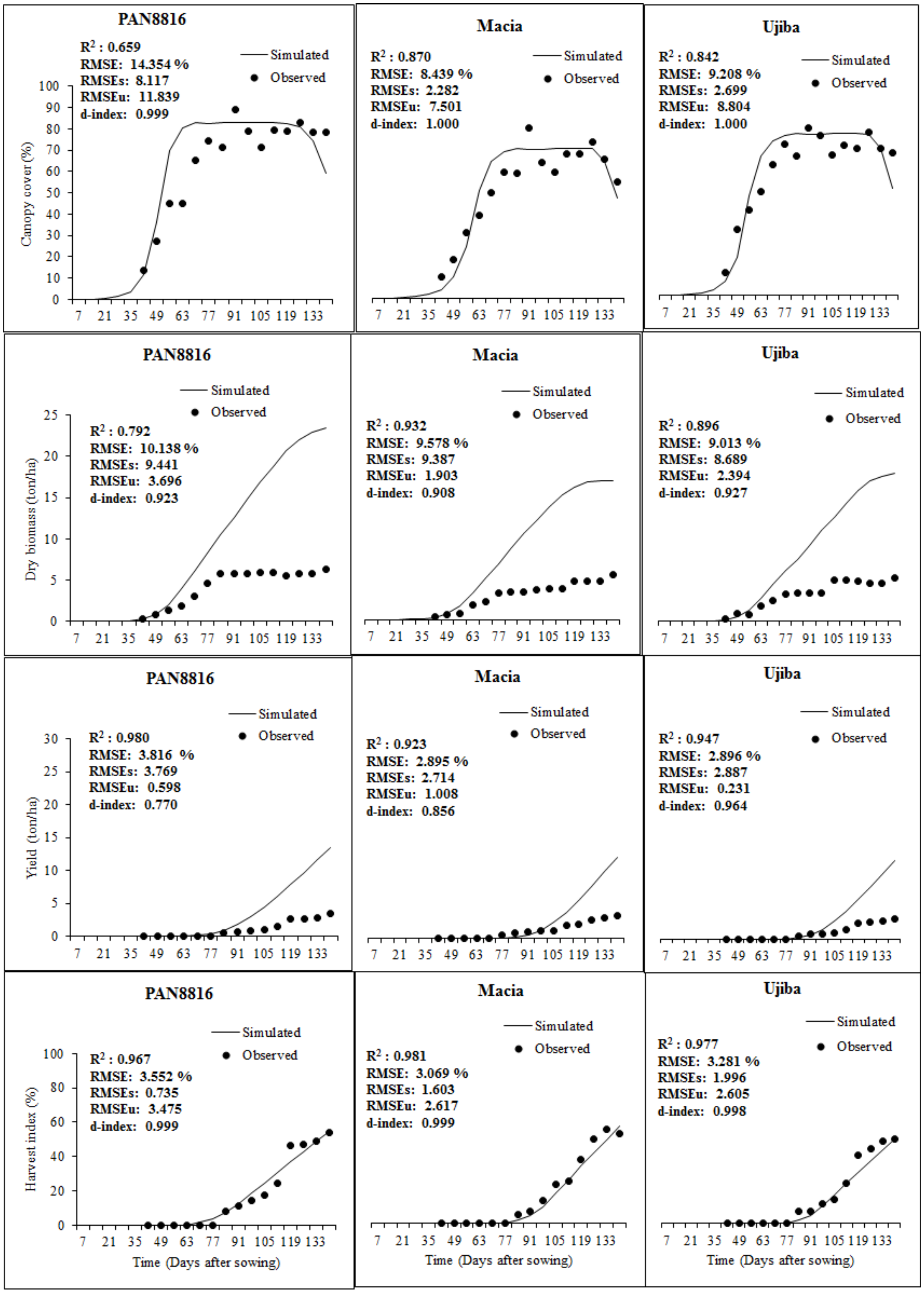

Figure 9: Simulated vs. observed canopy cover, biomass, yield, and harvest index for PAN8816, Macia and Ujiba sorghum genotypes for the calibration model run using 2013/14 Ukulinga growing season data.

Testing

There was a good agreement ($R^2 \geq 0.710$; RMSE $\leq$ 22.73%; d $\geq$ 0.998) between observed and simulated crop canopy cover for all genotypes and planting dates. This showed that the model was capable of simulating canopy cover under different environments (Figure 2). This confirmed model robustness and consistency across environments. Once canopy senescence was triggered, the model simulated rapid canopy decline whereas in reality sorghum's canopy decline was moderate. This is because sorghum genotypes evaluated in the study employed osmotic adjustment and quiescence strategies which allowed for moderate canopy decline. The limitations of the model in capturing this aspect of sorghum resulted in a low goodness of fit between model simulated and observed values, especially under water stress.

With respect to the planting dates, the model simulated canopy cover well for early planting ($R^2 \geq 0.843$; RMSE $\leq$ 13.91%; d $\geq$ 0.999) and late planting ($R^2 \geq 0.873$; RMSE $\leq$ 12.07%; d $\geq$ 0.999) (Figure 2). Model performance was satisfactory ($R^2 \geq 0.710$; RMSE $\leq$ 22.73%; d $\geq$ 0.998) for the optimal planting. Model performance for the optimal planting date was affected by observed low emergence at optimal planting due to low soil water availability during and shortly after sowing. This resulted in observed low canopy cover compared to model simulated canopy cover (Figure 2). In this instance, the model could be used to assess gaps between actual and potential canopy cover under field conditions.

In field trials, time to physiological maturity was observed when a dark spot appeared on the opposite side of the kernel from the embryo signalling completion of dry matter accumulation (Eastin, Hultquist, & Sullivan, 1973). However, physiological maturity in model simulations was observed as when dry matter accumulation ceased. Under field conditions, physiological maturity occurred when canopy cover was relatively high while for model simulations it coincided with relatively low or zero canopy cover. This resulted in a slight overestimation ($\leq$ 7.8%) of time to physiological maturity in the model (Table 4). Since AquaCrop uses canopy cover to estimate transpiration and calculate biomass accumulation, this potentially led to a carry-over error in simulated biomass and yield. This would account for the over–estimation of the two parameters. Adjusting canopy sensitivity to water stress (canopy expansion, stomatal closure, early senescence and harvest index) could potentially improve model simulation, especially during canopy senescence where model simulations were less than satisfactory. However, the relative satisfactory of the model with minimum calibration confirms model simplicity and robustness and its suitability for use in areas with limited data sets.

AquaCrop separates the yield is separated into biomass and harvest index (Raes et al., 2009b), where harvest index is the ratio of economic yield over total aboveground biomass. Biomass accumulation is calculated as a product of WP and transpiration. Thereafter, biomass partitioning into yield is a function of harvest index. Prediction of biomass ($R^2 \geq 0.900$; RMSE ≤ 10.45%; d ≥ 0.850) and yield ($R^2 \geq 0.886$; RMSE ≤ 5.571%; d ≥ 0.918) was very good (Figures 3 and 4). However, the model significantly over–estimated both biomass and yield to generally be twice the observed values. On average, total biomass simulated by the model was 24.04, 20.68 and 20.70 ton/ha, whereas observed biomass was 10.82, 10.36 and 6.09 ton/ha for early, optimal and late planting dates respectively. Total yield simulated by AquaCrop was 12.24, 9.8 and 10.79 ton/ha, whereas observed yield was 5.25, 5.31 and 3.16 ton/ha for early, optimal and late planting dates respectively (Table 4). Expected sorghum yields are 3–8 ton/ha for genotypes used in the study. This implies that observed biomass and yield were within expected yields, whilst confirming that the model simulations over–estimated. Good canopy simulation by the model resulted in confidence in transpiration predictions used in biomass calculation. Model simulations exhibited differential water stress levels across planting dates, with highest water stress levels during the late planting date for all genotypes. This implies that water stress played a major role in biomass and yield determination. Determining the genotype–specific water stress co–efficients (Ks) could potentially improve yield model simulations. A default sorghum WP parameter (33.3 g/m^2) was used in simulations. This potentially did not contribute as a source of error in calculating biomass and subsequently yield since WP for c4 cereal crops is accepted to be 30–35 g/m^2 (Raes, Steduto, Hsiao & Fereres, 2010).

Trials used for calibration were planted late and not under an optimal planting date scenario, and this resulted in low and irregular rainfall more especially at grain filling stage as winter season approached. A heavy hailstorm in early January 2014 destroyed the initial trials designed for calibration. Thereafter, a late planting date trial was planted to develop calibration parameters. This potentially resulted in relatively lower maximum canopy cover, and distorted observations of time to maximum canopy cover, biomass, yield and reference harvest index observation. Despite this, canopy cover for three genotypes during calibration trials achieved at late planting (80–89%) suggest that reduction and distortions in observed measurements were not significant. This is because sorghum is not expected to achieve full canopy cover even under optimal conditions. Developing calibration parameters under optimal planting time (November– early December) could potentially improve model simulation of biomass and yield, albeit not significantly.

For the interest of comparison with previous work, simulations obtained from experimental sorghum genotypes were compared to those obtained from simulations using the AquaCrop default sorghum file. In comparison, simulations using the default file instead of three study genotypes exhibited excellent predictions of yield ($R^2 \geq 0.816$; RMSE $\leq 1.90\%$; $d \geq 0.900$) with relatively low overestimation error (23.0–109.2%). Yield overestimation error was low (23.0% and 27.2%) for early and optimal planting date respectively, where rainfall was relatively high and well distributed across planting season. For late planting date when relatively low, highly irregularly distributed rainfall was observed, yield overestimation was high (109.2%). Canopy cover was poorly simulated ($R^2 \geq 0.11$; RMSE $\leq 41.03\%$; $d \geq 0.995$) suggesting that canopy characteristics of local genotypes differ significantly from those of the AquaCrop default crop file. This highlights the need to perform additional experiments to determine canopy sensitivity to water stress for calibration of the three genotypes used. Since AquaCrop is a canopy level, yield response to water model, it is primarily important to predict accurately canopy cover in order to predict biomass and yield.

Table 9: AquaCrop simulated (Sim.) and experimentally observed (Obs.) time to physiological maturity in three sorghum genotypes planted at different planting dates. MOM stands for model overestimation margin.

		Time to physiological maturity			**Biomass**			**Yield**		
Planting date	**Genotype**	**Obs. (days)**	**Sim. (days)**	**MOM (%)**	**Obs. (ton/ha)**	**Sim. (ton/ha)**	**MOM (%)**	**Obs. (ton/ha)**	**Sim. (ton/ha)**	**MOM (%)**
Early	PAN8816	133	140	5.3	10.95	25.14	129.6	5.31	13.28	150.1
	Macia	140	140	0	11.70	23.47	100.6	6.38	12.35	93.57
	Ujiba	140	140	0	9.80	23.50	139.8	4.07	11.08	172.23
Mean		**138**	**140**	**1.8**	**10.82**	**24.04**	**122.2**	**5.25**	**12.24**	**132.9**
Default sorghum file					**10.82**	**19.54**	**80.6**	**5.25**	**6.68**	**27.2**
Optimal	PAN8816	126	133	5.6	9.87	21.54	118.2	4.99	10.33	107.0
	Macia	140	134	–4.3	11.28	20.19	79.0	6.79	10.2	50.22
	Ujiba	126	135	7.1	9.93	20.30	104.4	4.16	8.88	113.5
Mean		**131**	**134**	**6.35**	**10.36**	**20.68**	**99.6**	**5.31**	**9.80**	**84.50**
Default sorghum file					**10.36**	**18.67**	**80.2**	**5.31**	**6.53**	**23.0**
Late	PAN8816	126	135	7.1	5.00	20.44	308.8	2.71	10.75	296.7
	Macia	133	140	5.3	6.33	20.27	220.2	3.26	10.99	237.1
	Ujiba	126	140	11.1	6.93	21.38	208.51	3.50	10.64	204.0
Mean		**128**	**138**	**7.8**	**6.09**	**20.70**	**240.0**	**3.16**	**10.79**	**241.92**
Default sorghum file					**6.09**	**18.67**	**206.6**	**3.16**	**6.61**	**109.2**

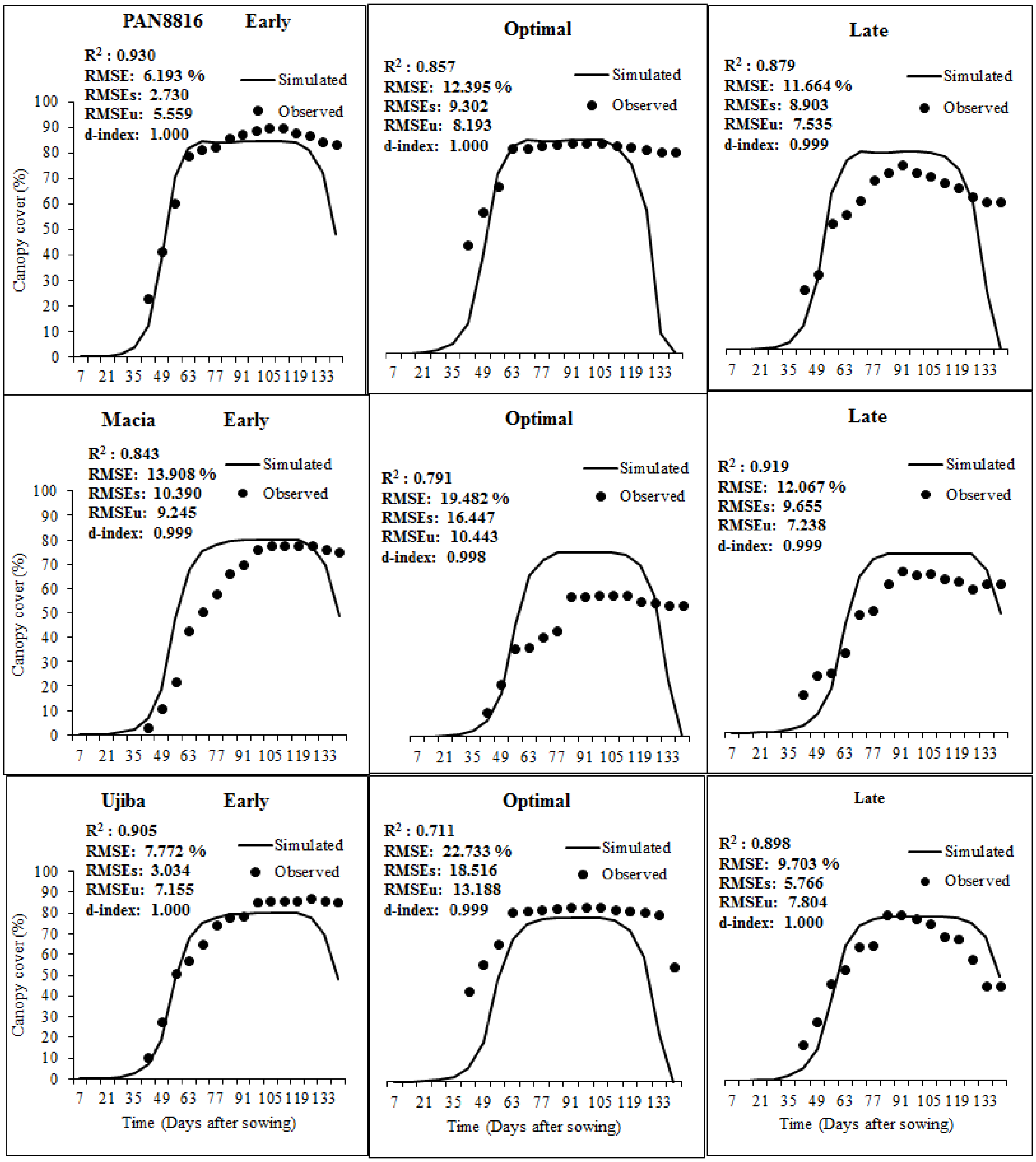

Figure 10: AquaCrop simulated and field observed canopy cover for PAN8816, Macia and Ujiba sorghum genotypes planted at three different planting dates (early, optimal and late) within the 2014/15 growing season at Ukulinga.

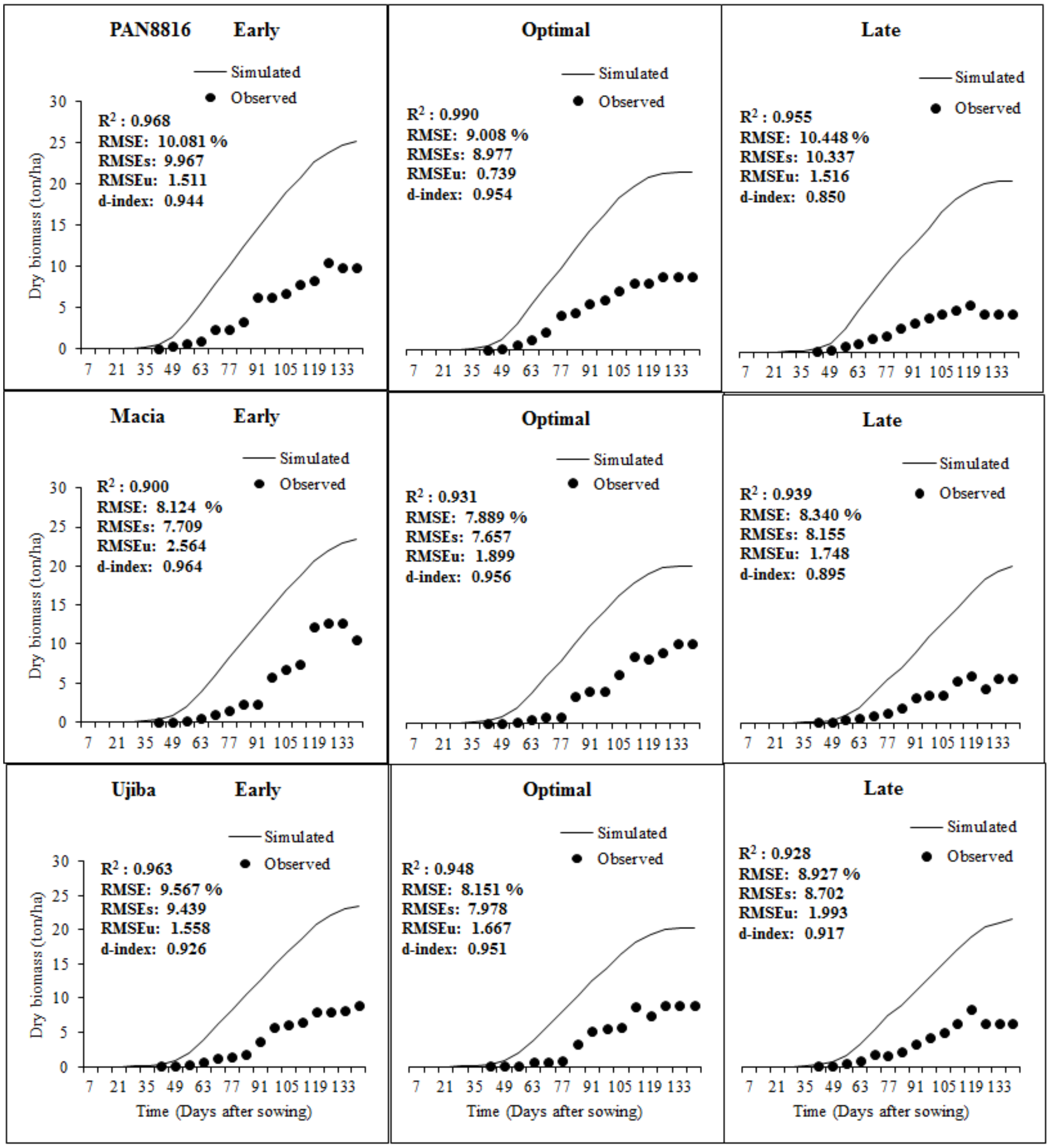

Figure 11: AquaCrop simulated and field observed aboveground dry biomass for PAN8816, Macia and Ujiba sorghum genotypes planted at three different planting dates (early, optimal and late) within the 2014/15 growing season at Ukulinga.

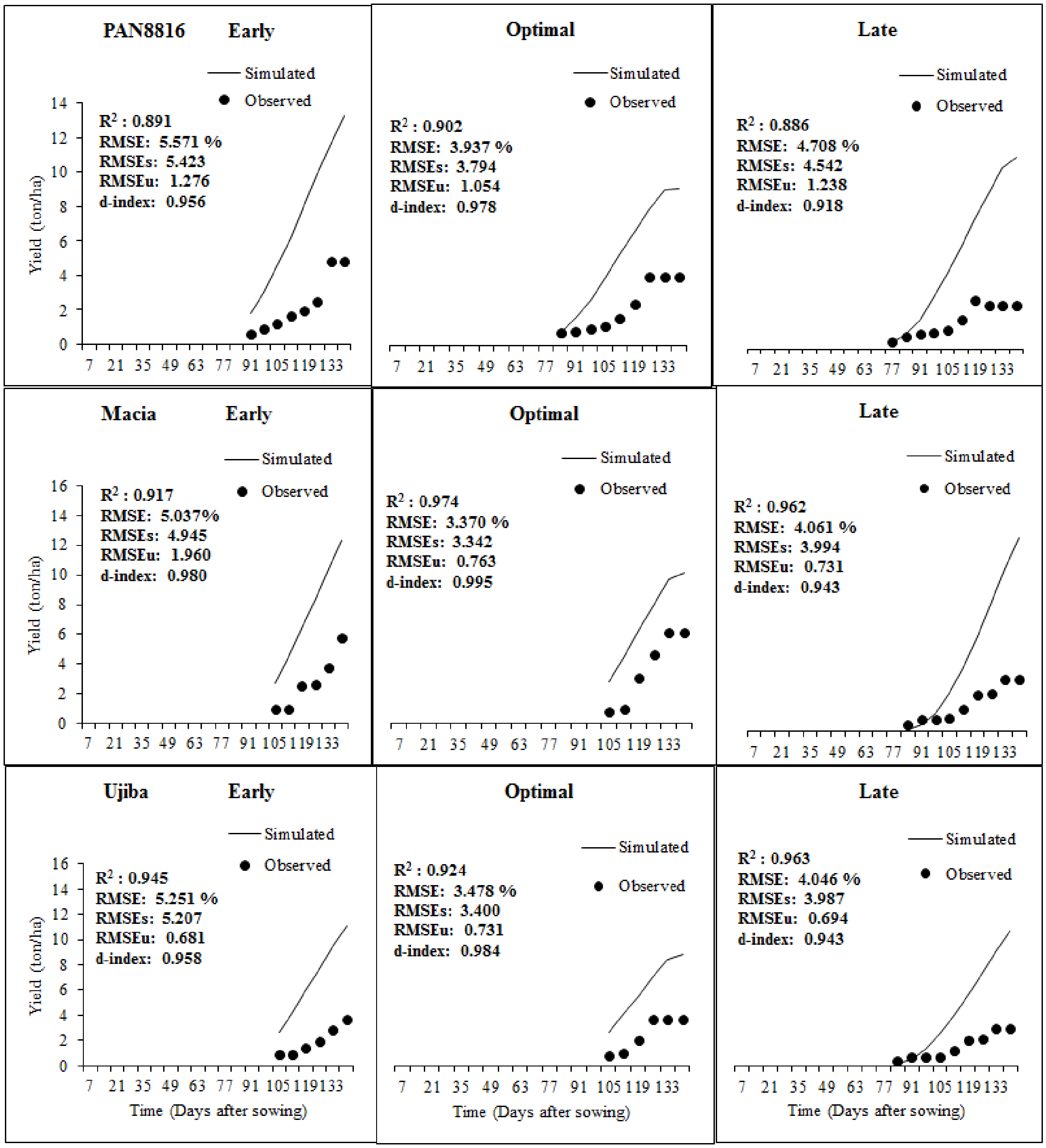

Figure 12: AquaCrop simulated and field observed panicle yield for PAN8816, Macia and Ujiba sorghum genotypes planted at three different planting dates (early, optimal and late) within the 2014/15 growing season at Ukulinga.

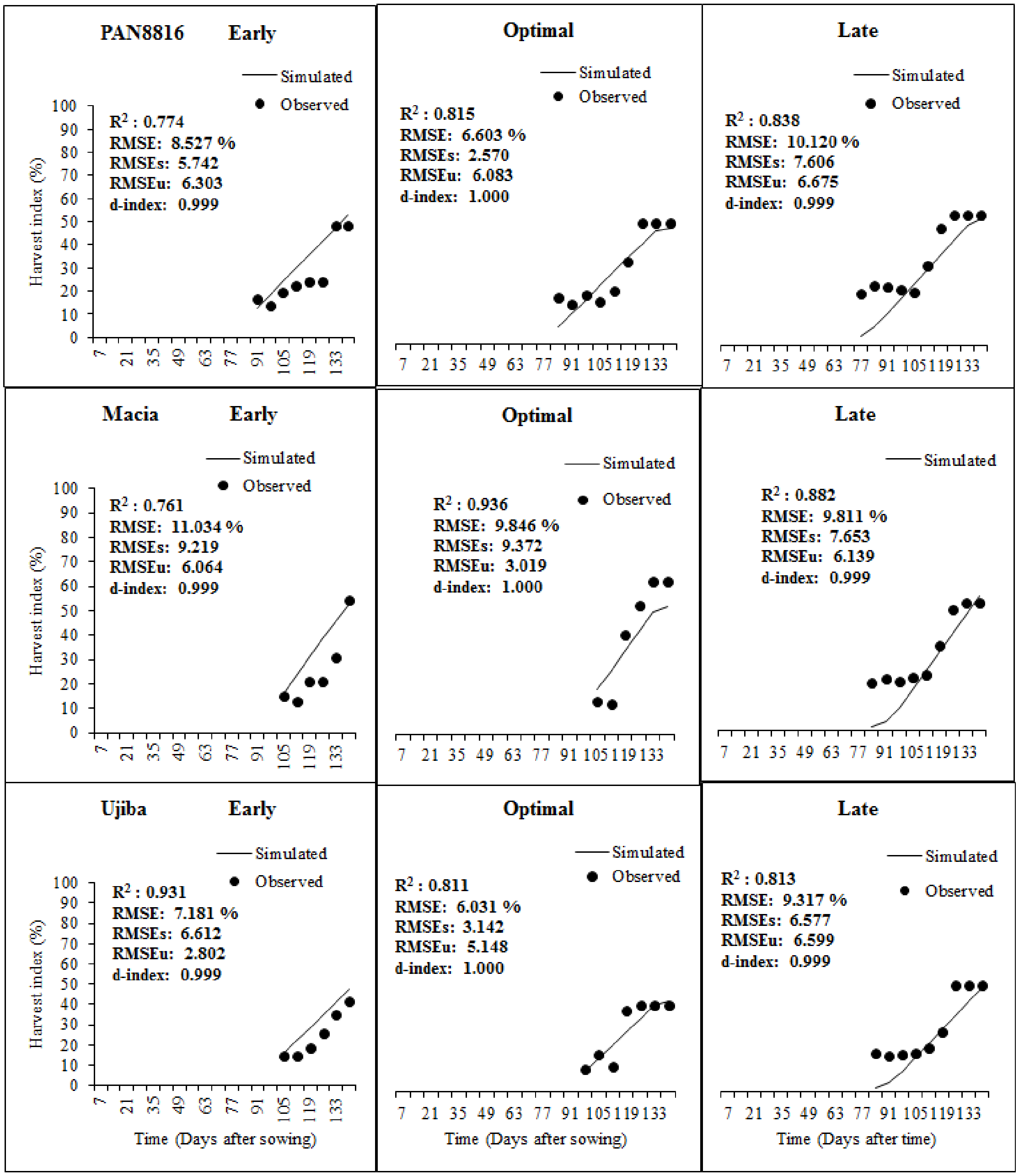

Figure 13: AquaCrop simulated and field observed harvest indices for PAN8816, Macia and Ujiba sorghum genotypes planted at three different planting dates (early, optimal and late) within the 2014/15 growing season at Ukulinga.

Despite the limitations in calculating biomass, the model was able to capture build–up of harvest index very well (($R^2 \geq 0.774$; RMSE $\leq$ 10.120%; d $\geq$ 0.999; Figure 5). This implies that the contribution of harvest index as a source of error in over–estimation of yield was minimal. Model over-estimation of biomass and yield increased for late planted sorghum genotypes, where water stress was observed to be relatively high in comparison to other planting dates under experimental field trials and simulations. This suggests that canopy sensitivity to water stress should also be accurately described when calibrating the model for local sorghum genotypes. Developing genotype specific Ks values for the sorghum genotypes used in this study could improve model simulations of biomass and yield. Overall, canopy cover, biomass, harvest index and yield model simulations were very good for all genotypes and planting date environments.

Conclusion

The model was able to simulate canopy cover, biomass accumulation, harvest index and yield relatively well for all sorghum genotypes and planting dates. The model did not accurately capture sorghum canopy decline as it did not consider sorghum's quiescence growth habit which allows for delayed canopy senescence under water–limited conditions. Studies to develop parameters for canopy sensitivity to water stress could improve canopy simulations. The model over–estimated biomass and yield, especially for the late planting date when severe water stress was observed under field conditions. Over–estimation of biomass, and consequently yield, was attributed to the default Ks parameter which may not be representative of sorghum genotypes used in this study. Therefore, future studies should develop Ks values for local genotypes. Furthermore, developing calibration parameters under optimal planting time scenarios could potentially improve model simulation. Despite the limitations in model performance, the model confirmed sorghum drought tolerance and its viability for production under water limited conditions. The relatively good simulations produced by the ten step calibration confirm AquaCrop's simplicity and suitability for use in places where extensive data sets may be unavailable. Biomass and yield overestimation resulting from the use of the ten step calibration procedure suggests that other parameters (canopy sensitivity to water stress, planting time for calibration trials, and Ks) are required to improve canopy and yield predictions for sorghum genotypes. However, the ten step calibration procedure is sufficient for predicting sorghum yield response water if limitations discussed in this study are considered.

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CHAPTER 6

SORGHUM BEST MANAGEMENT PRACTICES BASED ON AQUACROP PLANTING DATES SCENARIO ANALYSIS

*Sandile T. Hadebe, Tafadzwanashe Mabhaudhi and Albert T. Modi

Crop Science, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu–Natal, Private Bag X01, Scottsville 3209, Pietermaritzburg, South Africa; Tel: +27332605447; Fax: +27332606094; Corresponding author email: hadebesta@gmail.com.

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Abstract

Water–driven crop models are useful tools for predicting yield response to water availability, particularly under water limited conditions. The objective was to apply a well–calibrated and tested model to formulate best management recommendations for rainfed sorghum production in three different agro–ecologies of KwaZulu–Natal, South Africa (Ukulinga, Deepdale, and Richards Bay). The FAO AquaCrop model was used to generate planting dates for the different agro–ecologies based on onset of rainfall. Ten planting dates were selected for model simulations. Crop files for two sorghum genotypes Ujiba (landrace) and PAN8816 (hybrid) were considered for model simulations. Soil and climate files for each agro–ecology were developed from observed data. Climate files considered 10 year historical data. Simulations considered biomass, yield, water use and harvest index. Differences in biomass, yield, harvest index and water productivity were highly significant ($P<0.001$) between agro-ecologies. The model was able to simulate satisfactorily sorghum yield and water use at all three agro–ecologies. Seasonal rainfall, run–off, amount of soil evaporation, crop transpired water, and ground canopy cover were identified as key parameters influencing sorghum yield and water use. Tactical, strategic and operation management decisions were recommended to improve sorghum water use. Rainwater harvesting and its use in supplementary irrigation was suggested to improve agricultural water supply. Increasing planting population, applying mulching, intercropping with low water requirement crop as live mulch were recommended to improve ground cover, transpiration, and decrease runoff. Low tillage farming practices are suggested to conserve soil moisture and increase soil cover. Contour farming, ridge and mound tillage, strip farming and terrace farming are options that are suggested to reduce run-off during extreme rainfall events. Extent at which each strategy is used largely depends on rainfall per growing season and evaporation, which differ per agro-ecology and planting date.

Keywords: agro–ecologies, evapotranspiration, transpiration, evaporation, water productivity.

Introduction

About 95% of agriculture in sub–Saharan Africa is primarily rainfed (Singh *et al.,* 2011) with about 70% of the population relying on agriculture for food and livelihoods (Livingston *et al.*, 2011). Under these conditions, unfavourable weather conditions due to climate change and variability (Tsheko, 2003) increase the incidence of food insecurity. This negatively impacts resource–poor farmers whose livelihoods depend mainly on agriculture (Tadross *et al*., 2005). In addition, the inability of this group of farmers to adapt to changing or variable weather patterns makes them increasingly vulnerable and prone to repeated episodes of crop failure and food insecurity. For farmers relying on rainfed agriculture, the ability to adapt to changing and/or variable weather patterns on a season–to–season basis is a prerequisite to successful crop production. There are various strategic and tactical decisions that can allow for farmers to adapt to changing and variable weather patterns. On a tactical level, these include crop or cultivar choice and planting date selection.

Traditionally, farmers use the onset of the rainy season as the criteria for setting planting dates. However, there is much variation as to how resource–poor farmers define this criterion. This often results in farmers experiencing mixed fortunes and also making them inflexible as their criteria seldom changes from season to season. Onset of rainy season has become unpredictable and mostly delayed over the past decades (Leary *et al*., 2008; Loo *et al*., 2014; Patwardhan *et al*. 2014). Onset of rainfall is one of the most important occurrences for the farmer. Early onset allows farmers to plough the land and plant early and benefit from low evaporative demand, while late onset can result in crop sensitive stages coinciding with unfavourable periods (Moeletsi *et al*., 2011). The start and end of the rainy season define the length of the rainy season which strongly determines the success or failure of rainfed crops. In addition, the quality of the growing season, as indicated by the length and severity of within–season dry spells, will also influence the yield gap and can often cause total crop failure (Geerts *et al*., 2006).

It is therefore important to determine, at a reasonable accuracy, the probability levels of the onset of rains, cessation of rains and length of rainy period, as well as their inter-relationships, in order to assist in planning of dryland farming activities (Moeletsi and Walker, 2012). Informed decision making for optimum management practices such as cultivar choice, planting dates and fertiliser application rates can contribute to increased yields under rainfed conditions. Optimum management practices can be evaluated using validated models as within–season and seasonal decision support tools (Boote *et al*., 1996; Kang *et al*., 2009; Lobell and Burke, 2010). In the current study, an established water–driven model, AquaCrop (Steduto *et al*., 2009; Raes *et al*., 2009), was applied for a range of agro–ecologies across KwaZulu–Natal to assist with generating best practice management recommendations for cultivar choice and planting date selection.

Materials and Methods

Study Site Descriptions

Three agro-ecologies (Deepdale, Richards Bay and Ukulinga) across KwaZulu–Natal province were selected based on access to and differences in long–term meteorological data and soil information (Table 1). Daily data for Ukulinga meteorological parameters was obtained from an on–farm (within 100 m radius) automatic weather station courtesy of Agricultural Research Council – Institute for Soil, Climate and Water (ARC–ISCW). Daily meteorological data for Deepdale and Richards Bay were obtained courtesy of the South African Sugar Research Institute (SASRI) weather station located within a 10 km radius from field trial agro-ecologies. Weather data obtained were minimum and maximum temperature, rainfall, and reference evapotranspiration. Weather parameters obtained were used to create climate files and input into AquaCrop.

Model Parameterisation

Simulations were performed using AquaCrop (Version 4.1). Climate files for each of the selected agro–ecologies were developed using daily weather data for maximum and minimum temperatures, rainfall and reference evapotranspiration. Long–term weather data for each of the agro–ecologies were obtained via the ARC–ISCW and SASRI network of automatic weather stations. These were then used to develop separate temperature (.TMP), rainfall (.PLU) and reference evapotranspiration (.ETO) files in AquaCrop. For CO_2, AquaCrop's default CO_2 file measured at Mauna Luau was used; thereafter, climate files (.CLI) were developed for each agro–ecology and input into the model.

Table 10*:* Soil and climate descriptions for the three agro–ecological zones.

	Deepdale	**Richards Bay**	**Ukulinga**
Geographical location	28º01'S; 28º99'E	28°19'S; 32°06E	29º37'S; 30º16'E
Altitude (m a.s.l.)	998	30	775
Bio-resource group	Coast hinterland thornveld	Moist coast forest, thorn and palmveld	Moist coast hinterland and ngongoni veld
Annual rainfall	750 – 850 mm	820 – 1423 mm	694 mm
Average temperature	18.4°C	22°C	17°C
Frost occurrence	Moderate	None	Light and occasional
Soil texture class	Clay	Sand	Clay
Clay content	53%	< 5%	< 29%
Soil type	Jonkersberg form (Jb)	Inhoek form (Ik)	Chromic luvisols
Field capacity (%)	46.2	10.9	46.3
Permanent wilting point (%)	34.7	6.2	23
Saturation (%)	50	47.1	46.7
Soil profile depth (m)	>1	>1	0.6

AquaCrop already has a default sorghum crop file. For the current study, the default file was fine–tuned to develop two separate sorghum crop files (.CRO) for PAN8816 and Ujiba sorghum. Fine–tuning was done using data derived from field trials conducted during 2013/14 season at Ukulinga Research Station. Briefly, Ujiba is a landrace of which they are usually preferred by rural farmers for production because they do not have to repurchase seed every year. PAN8816 is a hybrid variety preferred for production by commercial farmers. Details of model parameterisation and testing were reported in Chapter 5. Thereafter, the crop files were input into the AquaCrop database.

Similar to other established models, AquaCrop requires a detailed soil file for the selected location. Soil files (.SOL) for each of the selected agro–ecologies were developed using information described in Table 1 and input into AquaCrop.

Development of Planting Scenarios in AquaCrop

AquaCrop was used to develop planting scenarios according to Mizha *et al*. (2014). First sorghum planting occurs around the first week of September in KwaZulu–Natal, soon after the first spring rains. Latest planting usually occurs by end of January (Mlambo 2014; Nkala 2014 *Personal communication*). The Department of Agriculture, Forestry and Fisheries (DAFF, 2010) recommends optimal planting time for sorghum from start of November until end of December in South Africa, with dates falling on either side of the recommended times regarded as early and late planting, respectively. The first planting date can be defined as the first rainfall event capable of supporting germination (Keatinge *et al*., 1995). All simulation runs were started on the first day of September in each season, before the start of the rainfall season and assuming a bare soil. In this study the first planting date of the season was defined according to the Agricultural Research and Extension (AREX) criterion (Raes *et al*., 2004) which defines a planting date as the occurrence of 25 mm rainfall in 7 days after the initial search date, the first planting date in this case (Mizha *et al*., 2014). This ensures there is enough soil water, not only for germination but also to sustain the crop through the early development stage (Moeletsi and Walker, 2012).

As a result of variability in rainfall amount, distribution and subsequently onset of rainfall season, the number and spread of planting days generated by AquaCrop varied across agro-ecologies. For purposes of the current study, at most ten planting dates per site with an average two planting dates per month, were used for model scenario analyses (Table 2).

Model Simulations

Climate, crop and soil files were input into AquaCrop Version 4.1. Management file was set to run for rainfed crop production. Planting dates were varied based on times generated by the model using user defined criteria as described in above. Thereafter, model runs were performed.

Model Evaluation

Model inputs for weather and model outputs were analysed using GenStat® (Version 16, VSN International, UK) as well as using descriptive statistics and Box and whisker plots computed using Microsoft Excel®.

Table 11: AquaCrop simulated planting dates using AREX criteria for three different agro–ecologies.

Planting date number	Deepdale	Richards Bay	Ukulinga
1	29 October	15 September	7 September
2	19 November	29 September	26 September
3	1 December	18 October	22 October
4	7 December	18 November	27 October
5	12 December	23 November	11 November
6	21 December	29 November	24 November
7	25 December	23 December	10 December
8	1 January	2 January	20 December
9	3 January	3 January	10 January
10	11 January	30 January	15 January

Results and Discussion

Fitting sorghum into different agro-ecologies

Rainfall received during the growing period, as simulated by AquaCrop, varied significantly ($P<0.001$) between planting dates across different agro-ecologies. For the simulated agro–ecologies, Ukulinga received high rainfall for all simulated planting dates followed by Deepdale and Richards Bay, respectively (Table 3). Differences in biomass, yield, harvest index and water productivity were highly significant ($P<0.001$) between individual agro-ecologies. AquaCrop separates water use [evapotranspiration (ET)] into transpiration (T) and soil evaporation (E). In terms of plant growth and biomass production, transpiration is productive water loss as it is directly exchanged for biomass, while evaporation represents unproductive water loss (Mabhaudhi et al., 2014). Water losses to soil evaporation at Ukulinga (154 – 224.6 mm) and Richards Bay (136.6 – 210.1 mm) were higher than water transpired (130.9 – 209.4 and 36.7 – 88.8 mm). The opposite was true for Deepdale where transpiration (Table 5) was higher than evaporative water losses (Table 4); this translated to significantly ($P<0.001$) higher biomass and yield compared to Ukulinga and Richards Bay, respectively. High variability in rainfall, soil evaporation and transpiration at Richards Bay resulted in low and irregular yields as well as low water productivity (Figure 1).

Consequently, there was a higher frequency of crop failure for Richards Bay compared to Ukulinga and Deepdale agro–ecologies were there was no crop failure (Figure 3 and 4).

From the results of this study, production of sorghum is suited for Deepdale and Ukulinga agro-ecologies. There is adequate rainfall received during the growing period in Richards Bay (372.3 mm) for production of sorghum, however high evaporation losses (183.3 mm) resulted in low yield and crop failure (Figure 3 and 6.4) making Richards Bay unsuitable for sorghum production. High losses due to evaporation at all agro-ecologies can be significantly reduced using water retention, capture and storage strategies. Soil water retention strategies such as low tillage and mulching farming practices are recommended to reduce soil evaporation. Transpired water (<265 mm) in all agro-ecologies was a far cry from sorghum crop water requirements of 450–650 mm (FAO, 1991; Hensley *et al.,* 2000; Jewitt *et al.,* 2009) indicating that considerable and significant sorghum yield improvement can be achieved through effective irrigation using soil and rain water. Investing in rainwater harvesting infrastructure is a key element for all agro-ecologies to capture excess rainwater, especially for sorghum farming in Richards Bay where transpiration is low.

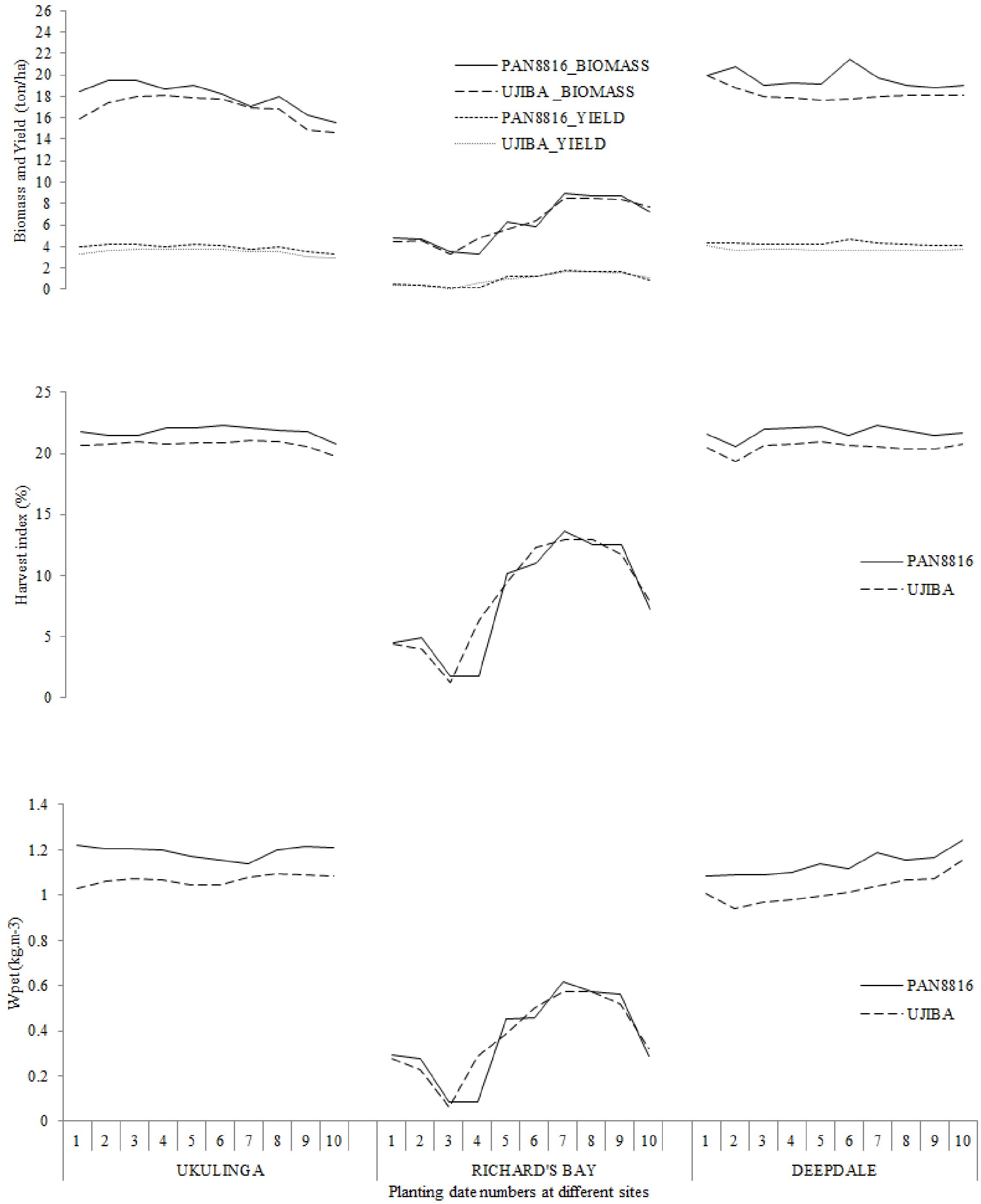

Figure 14: Mean simulated biomass and yield (A), percentage harvest index (B) and water productivity (C) for 10 planting dates at each of 3 agro-ecologies.

Table 12: Mean rainfall received during the growing season over a ten year period (2003–2013) for the three agro–ecologies. Rainfall is based on modelled output for rainfall received during the growing season.

Variety	Planting date	Ukulinga		Richards Bay		Deepdale	
		Mean	*SD	Mean	SD	Mean	SD
		(mm)					
PAN8816	1	507.1	88.2	269.6	98.7	543.0	67.7
	2	540.0	78.4	331.9	102.9	523.3	63.2
	3	535.7	85.5	335.7	130.6	478.6	73.0
	4	539.3	95.6	357.3	113.9	458.9	74.9
	5	525.0	229.2	364.2	124.2	433.2	71.5
	6	491.9	94.4	367.4	131.0	406.4	59.7
	7	445.3	115.3	421.3	199.5	394.1	66.6
	8	418.9	104.7	419.4	180.1	369.6	69.6
	9	335.7	103.3	450.2	184.7	343.9	61.2
	10	327.6	104.0	469.0	158.1	323.0	72.2
Ujiba	1	528.6	91.1	269.6	98.6	534.7	66.6
	2	559.5	77.5	302.2	106.2	517.1	62.7
	3	552.9	96.1	313.9	162.7	474.0	75.3
	4	548.0	96.5	313.9	113.9	456.2	72.8
	5	534.9	89.3	364.2	124.2	429.0	67.8
	6	500.3	105.7	367.4	131.0	403.9	60.8
	7	447.1	118.0	421.3	189.7	386.5	66.8
	8	420.7	103.8	419.4	180.1	357.9	68.8
	9	342.2	106.6	419.3	180.9	350.2	66.4
	10	312.1	100.8	469.0	158.1	317.4	64.7

*SD = standard deviation

Table 13: Simulated mean soil evaporation for PAN8816 and Ujiba sorghum varieties over a ten year period (2003–2013) for three agro–ecologies.

		Ukulinga		Richards Bay		Deepdale	
		Mean	*SD	Mean (m)	SD	Mean	SD
Variety	Planting date	(mm)					
PAN8816	1	225.6	33.8	136.3	20.5	223.6	15.9
	2	227.7	15.4	169.1	25.2	221.7	27.5
	3	231.4	12.9	173.2	28.7	214.4	26.1
	4	230.3	16.1	186.4	47.0	208.3	27.8
	5	229.2	21.9	186.9	49.2	194.6	29.6
	6	238.2	59.0	186.2	53.7	192.0	26.7
	7	204.3	14.0	194.7	60.7	185.0	20.8
	8	191.4	13.0	199.1	62.8	180.0	18.2
	9	166.9	14.3	205.8	66.6	167.7	17.1
	10	160.1	11.4	210.1	39.0	156.1	196.0
Ujiba	1	224.2	39.6	136.3	20.5	233.1	14.9
	2	220.5	20.30	155.5	24.8	230.1	27.7
	3	222.6	13.2	162.7	27.3	223.2	26.3
	4	222.2	16.6	186.4	31.2	218.6	27.0
	5	221.4	24.0	186.9	49.2	213.6	30.8
	6	232.1	64.5	186.2	53.7	200.8	27.1
	7	195.0	15.0	194.7	60.7	192.0	22.1
	8	182.9	12.9	199.1	62.8	172.0	18.6
	9	169.4	18.3	199.9	61.9	175.4	19.3
	10	154.0	26.2	210.1	39.0	153.4	15.3

*SD = standard deviation

Table 14: Simulated mean crop transpiration for PAN8816 and Ujiba sorghum varieties over a ten year period (2003–2013) for three agro–ecologies.

Variety	Planting date	Ukulinga		Richards Bay		Deepdale	
		Mean	*SD	Mean	SD	Mean	SD
		(mm)					
PAN8816	1	174.1	48.2	42.9	37.1	261.6	19.7
	2	190.9	32.5	46.5	37.4	237.7	32.3
	3	193.8	16.2	36.7	25.4	233.5	38.4
	4	194.8	16.1	53.6	54.4	218.6	35.9
	5	188.7	20.6	62.2	59.2	214.7	36.1
	6	162.0	59.7	70.3	62.8	209.6	25.2
	7	168.1	18.8	87.2	79.3	209.1	25.2
	8	163.9	17.2	86.4	81.8	195.1	14.5
	9	131.2	27.5	88.8	85.4	202.1	18.2
	10	125.5	23.9	80.6	77.1	196.0	20.7
Ujiba	1	188.4	54.6	42.9	37.1	243.5	18.1
	2	206.7	40.0	46.5	37.4	221.8	29.1
	3	209.3	17.5	36.8	24.9	208.2	34.7
	4	209.4	17.6	36.8	33.2	203.0	34.1
	5	200.9	22.6	62.2	59.2	198.9	34.4
	6	174.2	64.3	70.3	62.8	196.9	27.1
	7	179.9	22.0	87.2	79.3	197.2	22.4
	8	174.9	19.1	86.4	81.7	202.6	18.6
	9	142.8	29.7	85.9	81.2	190.0	17.3
	10	130.9	26.2	80.6	77.1	188.5	16.4

*SD = standard deviation

Effect of planting date selection on water use, biomass and yield of sorghum

Evaporation and transpiration significant ($P<0.001$) varied between planting dates which resulted in considerable differences ($P<0.001$) all four yield related parameters between individual planting dates in all agro-ecologies. Uneven and erratic rainfall distribution (Table 3) across planting dates accounted for differences in evaporation and transpiration.

Optimal planting dates at Ukulinga are between 7 September and 24 November as highest, stable yields (Figure 2 and 3) are achieved during the period. Planting later than these dates decreased biomass, yield and water productivity (Figure 1) and stability (Figure 2, 3 and 5) thereof. However, reasonable biomass (> 14 $ton.ha^{-1}$) and yields (> 3 $ton.ha^{-1}$) were achieved when planting later than optimal planting dates. Despite low observed yield and water use traits at Richards Bay, optimal sorghum yields were achieved when planting between 23 December and 3 January. Yields were unstable throughout planting dates at Richards Bay with high crop failure frequency, due to low irregular rainfall, high evaporation and low transpiration experienced by crops. In Deepdale, optimal planting time was achieved throughout simulated planting time, as yield and biomass were high and stable. Yield and water productivity were most stable when planting between 21 December and 3 January in Deepdale. Challenges of irregular and erratic rainfall on all planting dates can be mitigated by using long– and short–term water capture and storage strategies to capture and better use excess rainfall from storm events. Rainfall must be retained by techniques that reduce storm-water runoff, improve infiltration and increase the water storage capacity of the soil. Strategies that can help reduce runoff through improved infiltration capacity and soil transmission characteristics are: mulch farming, soil conditioning, and ploughing methods that keep the upper soil layers porous at least for a short time especially in compact soils that restrict root development and infiltration. On planting dates where yields are highly unstable and where a deficit exists in crop water requirements, supplementary irrigation using harvested rainwater and other external water sources should be explored to mitigate the challenge of insufficient transpired water.

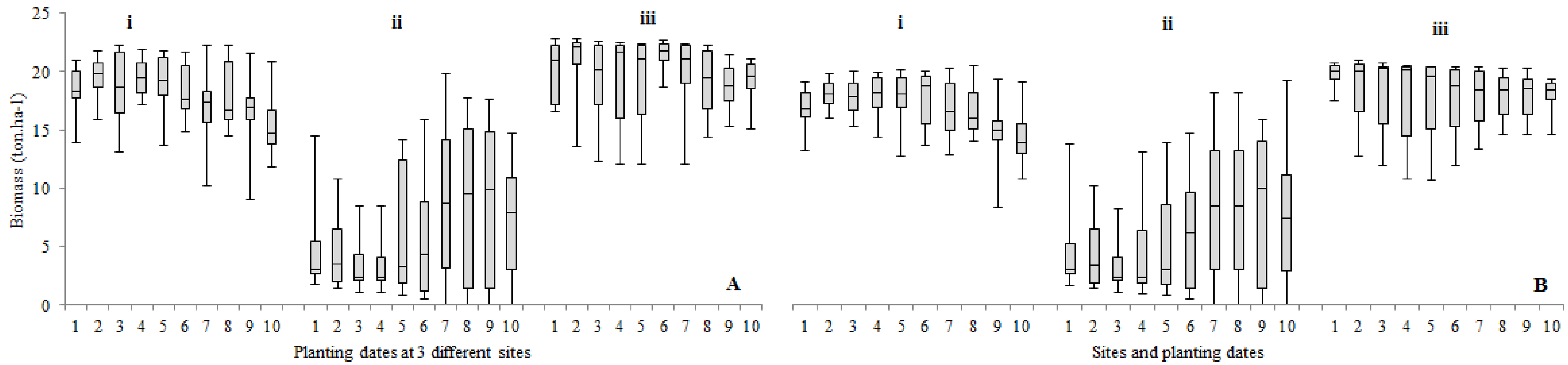

Figure 15: Biomass distribution for PAN8816 (A) and Ujiba (B) sorghum varieties simulated using AquaCrop for 10 planting dates at each of 3 agro-ecologies (i) Ukulinga, (ii) Richards Bay and (iii) Deepdale. Boxes delimit the inter-quartile range (25–75 percentiles) and whiskers show the high and low extreme values.

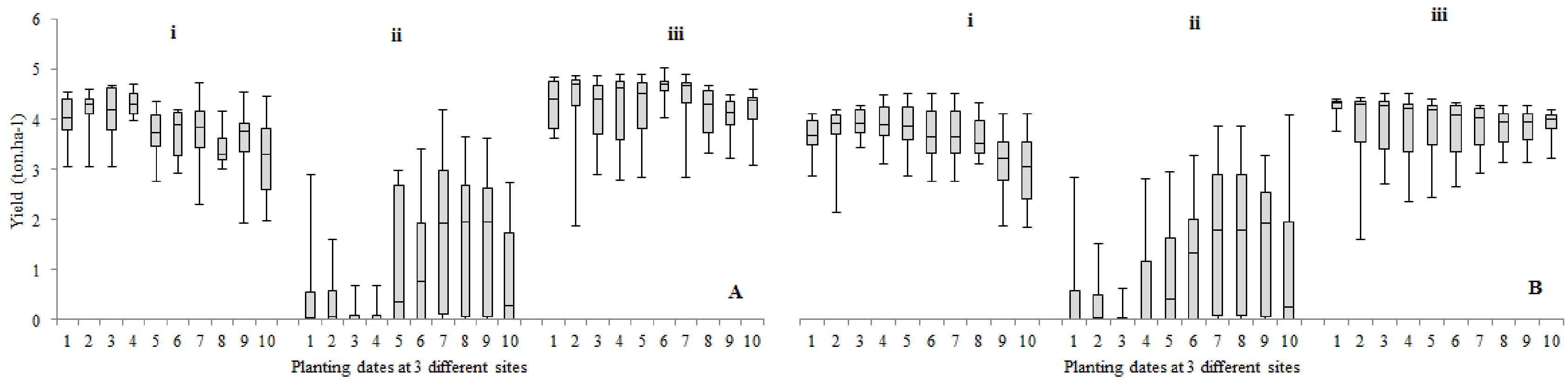

Figure 16: Yield distribution for PAN8816 (A) and Ujiba (B) sorghum varieties simulated using AquaCrop for 10 planting dates at each of 3 agro-ecologies (i) Ukulinga, (ii) Richards Bay and (iii) Deepdale. Boxes delimit the inter-quartile range (25–75 percentiles) and whiskers show the high and low extreme values.

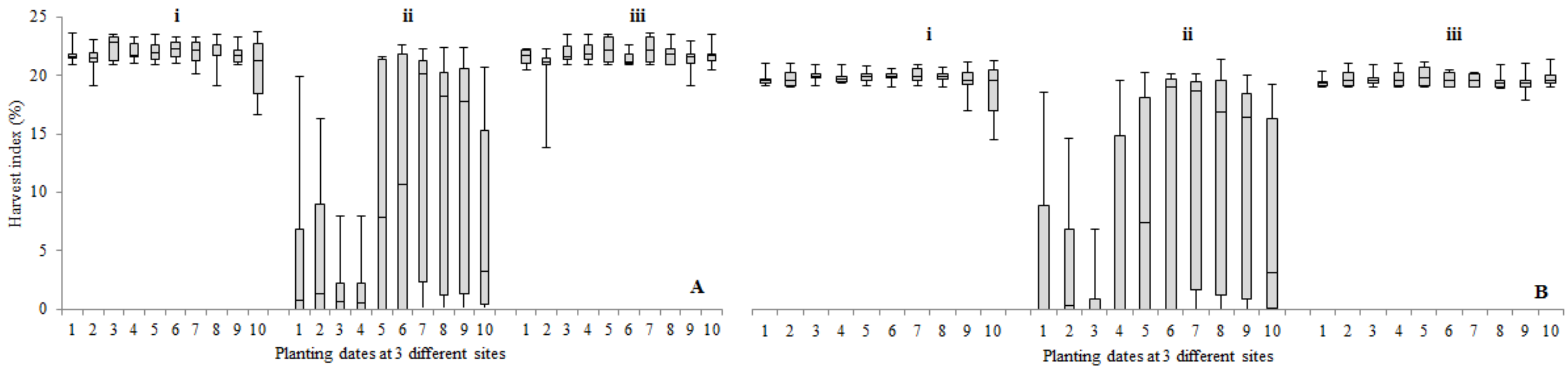

Figure 17: Harvest index distribution for PAN8816 (A) and Ujiba (B) sorghum varieties simulated using AquaCrop for 10 planting dates at each of 3 agro-ecologies (i) Ukulinga, (ii) Richards Bay and (iii) Deepdale. Boxes delimit the inter-quartile range (25–75 percentiles) and whiskers show the high and low extreme values.

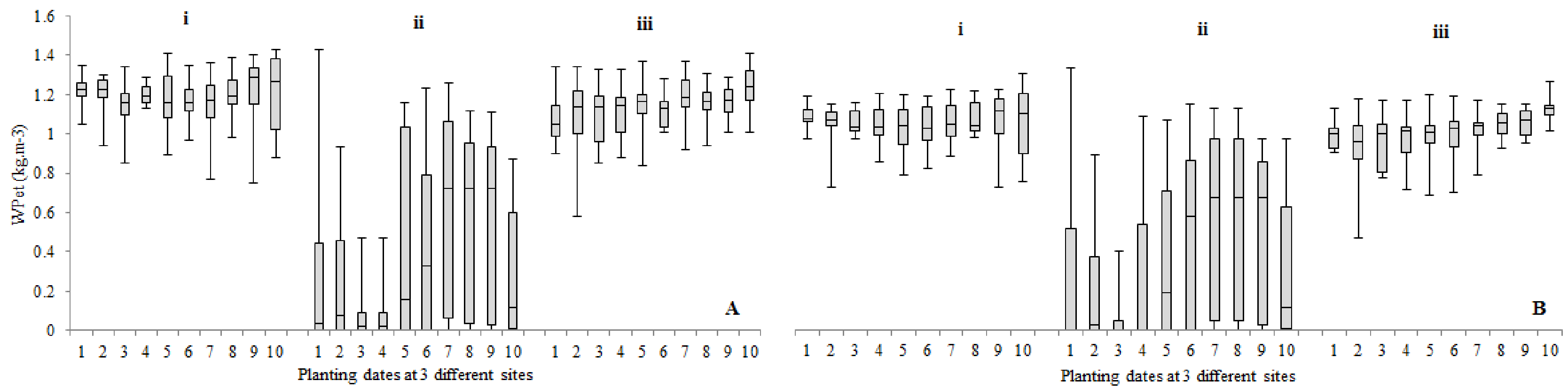

Figure 18: Water productivity (WPet) distribution for PAN8816 (A) and Ujiba (B) sorghum varieties simulated using AquaCrop for 10 planting dates at each of 3 agro-ecologies (i) Ukulinga, (ii) Richards Bay and (iii) Deepdale. Boxes delimit the inter-quartile range (25–75 percentiles) and whiskers show the high and low extreme values.

Yield and water use responses of sorghum varieties to agro-ecologies and planting dates. Evaporation and transpiration were similar (P>0.05) between PAN8816 and Ujiba sorghum varieties. This resulted in similar (P>0.05) biomass, yield, harvest index and water productivity in both varieties across planting dates and agro-ecologies. PAN8816 benefitted marginally from early emergence, high canopy cover and delayed senescence; this translated to higher biomass, yield, harvest index and water productivity (Figure 1) compared to Ujiba. Affording farmers can plant PAN8816 to benefit from higher yields, while resource–constrained farmers are recommended to grow Ujiba as yield losses are not significant when planting Ujiba as an alternative.

Possible Management Practices and Conclusions

- Transpired water (<265 mm) in all planting dates and production site scenarios was a far cry from sorghum crop water requirements (450 – 600 mm) which indicates that considerable yield improvement can be achieved through effective capture, storage, supplementary irrigation and reuse of rainfall water. Rainwater water harvesting can be used to capture rainfall during and outside the growing season. Richards Bay sorghum farmers would benefit most from such strategies as transpiration was low throughout planting dates, water scarcity linked crop failure occurred frequently and the agro-ecology has a longer rainfall season.
- Sorghum farmers in Deepdale and Ukulinga can explore increasing planting population to exploit high evaporated water. Increasing planting population however increases demand of soil nutrients and minerals, therefore appropriate soil fertilisation mechanisms are recommended with this strategy. In Richards Bay, farmers need not consider this strategy but focus on strategies that increase transpiration. Intercropping sorghum with a legume is recommended to effectively use evaporative water in all three agro-ecologies. Ideally, the legume of choice should have low water requirements and a short growing (≈90 days) season.
- Different levels of mulching and low tillage farming practices are suggested to conserve soil moisture and increase soil cover. Extent at which each strategy is used largely depends on rainfall per growing season and evaporation, which differ per agro-ecology and planting date. This strategy is especially recommended when farming sorghum outside optimal planting dates discussed in this study.
- Rainfall must be retained by techniques that reduce storm-water runoff, improve infiltration and increase the water storage capacity of the soil. Strategies that can help

reduce runoff through improved infiltration capacity and soil transmission characteristics are: mulch farming, soil conditioning, and ploughing methods that keep the upper soil layers porous at least for a short time especially in compact soils that restrict root development and infiltration

- Contour farming, ridge and mound tillage, strip farming and terrace farming are options that are suggested to reduce run-off during extreme rainfall events.

Acknowledgements

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CHAPTER 7

GENERAL DISCUSSION

7.1 Findings and Implications

Local cereal crops that have desirable water use characteristics are currently being overshadowed by the exotic crops in terms of production area, consumption trends and research attention. This has led to declining cereal yields in sub–Saharan Africa (SSA). Increasing research attention on drought–tolerant cereals such as sorghum assists in providing knowledge valuable in increasing cereal crop water productivity under arid and semi–arid regions of SSA. This study aimed to determine water use and water use efficiency of different sorghum genotypes as well as to model water use of such sorghum genotypes for extrapolation to similar rainfed agro–ecologies.

One critical question central to the study was the need to conduct a review of available knowledge on water use of cereals. The review found that of the range of cereals cultivated in SSA, sorghum was uniquely suited to production in arid and semi–arid regions. This was attributed to its high and stable water use efficiency, drought and heat tolerance, high germplasm variability, comparative nutritional value, and existing food value chain across SSA. Despite this, the review found that sorghum was socio–economically and geographically underutilized across much of SSA, especially in semi–arid and arid agro–ecologies where production it was most suited. The review concluded that sorghum inclusion and promotion in arid and semi–arid areas of SSA, especially among subsistence farmers, could improve water productivity and food security. However, its inclusion and promotion would require the availability of robust empirical information describing the water use (WU) and water use efficiency (WUE) of locally adapted varieties; this was shown to be lacking.

To this end, a series of field trials were conducted to determine WU and WUE across different environments (spatial and temporal). Measurement of WU and WUE from two contrasting sites environments (Ukulinga and Mbumbulu) showed that WU and WUE varied significantly between the two environments. This was attributed, in part, to differences in soil physical and hydraulic properties. Ukulinga is characterised by clay loam (< 29% clay content) soils while Mbumbulu soils are clayey (> 60% clay). This resulted in higher WUE at Ukulinga (11.01 kg ha^{-1} mm^{-1}) than Mbumbulu (7.49 kg ha^{-1} mm^{-1}). The fact that clay soils have poor drainage characteristics relative to loamy soils is well established in the literature. The fact that environments differ suggests the need for site–specific management practices that will maximise on WUE.

Measured water use efficiency was sub–optimal. Rainfall received and crop water use was below sorghum water requirements reported by Jewitt et al. (2009). It is also important to note that not all rainfall is taken up by the plant in exchange for biomass production. Water losses through soil evaporation, and possible runoff during storm events possibly resulted in unproductive water losses. Under such circumstances, strategies that minimise evaporative water loss, conserve soil water and maximise crop transpiration are recommended to optimize yield and WUE. Such strategies include intercropping and conservation agriculture which have been reported to improve WUE of dryland cropping systems (Chimonyo et al., 2015). Again, the use of site–specific management practices would be encouraged. However, despite the low rainfall, the fact that sorghum was capable of producing some yield, as opposed to crop failure, confirms its drought tolerance and suitability for production low rainfall agro–ecologies.

Another challenge in rainfed agriculture relates to selection of planting dates. Farmers either plant too early, exposing the crop to water stress during early establishment, or plant late, exposing the crop to stress during critical reproductive growth stages (Mabhaudhi and Modi, 2011). This also tends to affect crop water use and WUE as the two are linked to length of growing season and soil water availability. To this end, this study evaluated sorghum WU and WUE in response to different planting dates. The results confirmed that planting date selection remains a key tool for managing water stress under field conditions. Planting early resulted in more favourable WU and WUE relative to recommended optimal dates. This was due to longer season duration relative to the optimum and late planted crop whereby the rains petered out early, triggering a hastening of the crop cycle. Consequently, a shorter season duration resulted in lower biomass and yield. However, even under these circumstances, sorghum was still capable of producing reasonable yields. While these may appear low, they would be a significant contribution to household food security.

Sorghum genotypes adapted to low water availability through reduced canopy size and duration, low chlorophyll content index and stomatal conductance, and hastening phenological development. Low water availability was associated with low yields and WUE. Differential responses were observed in sorghum genotypes with respect to water availability. For PAN8816 and Macia, WUE decreased in response to low soil water content. By contrast, WUE for the Ujiba and IsiZulu landraces improved under low water availability. This re-affirms reports that landraces are suited to harsh environmental conditions (Mabhaudhi and Modi, 2015). Landraces therefore are a valuable germplasm resource for breeding for drought tolerance in sorghum.

Water use efficiency values for PAN8816 (5.69 – 12.41 kg ha^{-1} mm^{-1}), Macia (5.46 – 15.81 kg ha^{-1} mm^{-1}), Ujiba (5.02 – 13.36 kg ha^{-1} mm^{-1}) and IsiZulu (7.36 – 11.00 kg ha^{-1} mm^{-1}) genotypes obtained in the current study were higher than that of other major cereal crops (Chapter 2). This highlights the advantage of sorghum cultivation as an alternative cereal crop in improving water productivity in semi–arid and arid areas. It also suggests the possibility of improving WUE beyond the reported optimal values of 12.4 – 13.4 kg ha^{-1} mm^{-1} (Maman et al., 2003). This could be achieved through adoption of management practices that allow for increased biomass accumulation through increasing transpired water use in crops (Mabhaudhi and Modi, 2015). Sorghum is uniquely suited to address issues of water productivity and food security in rainfed agro–ecologies. Consistent with other observations, site specific management decisions to improve crop transpiration, water conservation, reduce run–off, improve plant available water and increase ground canopy cover could improve sorghum yield and water productivity. This could be achieved through modelling sorghum yield response to water and mapping sorghum water productivity for arid and semi–arid regions.

The need to conduct multi-site evaluation trials increases cost and time in research. In this regard, the use of crop models is appropriate as they can be applied to consider such scenarios, thus saving on time and cost (Mabhaudhi et al., 2014). The AquaCrop model satisfactorily predicted yield response to water of sorghum genotypes. The model is a canopy level model, and AquaCrop predicted sorghum canopy cover satisfactorily for variable rainfall scenarios. This confirmed model use of explicit and intuitive parameters to predict yield response to water, while maintaining sufficient balance between accuracy, simplicity and robustness (Steduto et al., 2009; Raes et al., 2009). Sorghum farmers can use the model and genotype specific parameters developed in this study in making tactical, strategic and operational management decisions to optimize sorghum yield and water use. The ease of obtaining minimal crop data used in calibration is encouraging to smallholder farmers and extension services for prediction of sorghum water use in decision making, even using genotypes not considered in this study.

A major aspect of the application crop models is their ability to be used to answer 'what if' and 'when' questions (Mabhaudhi et al., 2014). In this regard, following calibration and testing of the model, AquaCrop was applied to evaluate planting date scenarios across three different agro–ecologies. The model performed well for the range of agro–ecologies considered. Model simulations confirmed sorghum's suitability for rainfed agriculture in a range of environments. The ability of the model to simulate yield response to water of sorghum varieties also confirmed its robustness (Steduto et al., 2009) and suitability for extrapolation to rainfed agro–ecologies. This implies that the model can be used to extrapolate sorghum water productivity to agro–

ecologies other than that of initial calibration. Therefore, for semi–arid and arid agro–ecologies of SSA where soil and weather data are available, the use of crop modelling is recommended as a cost–effective, relatively accurate tool to predict sorghum yield response to water. Separation of water use into transpiration and evaporation was particularly useful in developing best management practices to optimize transpiration (productive water loss). The model did not accurately capture sorghum canopy decline as it did not consider sorghum's quiescence growth habit which allows for delayed canopy senescence under water–limited conditions. The model over–estimated biomass and yield, especially for the late planting date when severe water stress was observed under field conditions. Over–estimation of biomass, and consequently yield, was attributed to the default conservative WP parameter which may not be representative of sorghum genotypes used in this study. Therefore, genotype calibrations done in this study have to be used with the discussed limitations in mind. Adjustments for biomass and yield over–estimation are recommended during application to reflect close approximation to actual field conditions.

Seasonal rainfall, run–off, amount of soil evaporation, crop transpired water, and ground canopy cover were identified as key parameters influencing sorghum yield and water use. Tactical, strategic and operation management decisions to improve sorghum water use. Rainwater harvesting and its use in supplementary irrigation was suggested to improve agricultural water supply. Increasing planting population, mulching and intercropping with low water requirement crops as a live mulch were recommended to improve ground cover, transpiration, and reduce runoff. Minimum tillage farming practices are suggested to conserve soil water and increase soil cover. Contour farming, ridge and mound tillage, strip farming and terrace farming are options that are suggested to reduce run-off during in regions that experience flash floods.

7.2 Conclusions

This study set to determine water use characteristics and water use efficiency of different sorghum genotypes as well as to model water use of such sorghum genotypes for extrapolation to similar rainfed agro–ecologies. Sorghum genotypes were cultivated under sub–optimal rainfall and/or marginal soils, and managed WUE and yield relatively higher that of other major cereals. This confirms sorghum suitability to improve cereal water productivity in semi– and arid regions of SSA. Sorghum adaptation to marginal environmental conditions was attributed to adaptation through crop morphology, physiology and phenology. The observed differences between sorghum genotypes used in this study confirms the importance of cultivar selection as a tactical decision. AquaCrop simulated sorghum yield response to water satisfactorily for rainfed ecologies other than that of initial calibration. This implies that AquaCrop can be used to assess production options for sorghum with minimum input requirement. This study concluded that sorghum is uniquely suited for production under semi– and arid, rainfed agriculture systems.

7.3 Recommendations

This study highlighted the need to develop parameters for canopy sensitivity to water stress to improve model canopy simulations in local genotypes. Further experiments are also suggested to develop genotype specific water productivity parameters to improve model simulation of biomass and yield for local genotypes. Studies on nutritional value of sorghum are recommended in order to determine nutritional water productivity (NWP) of sorghum. This would determine how water limitation under rainfed production affects end–use of sorghum. There is a need to calibrate and test AquaCrop for other sorghum genotypes grown in SSA. An easily accessible database for genotype–specific calibration parameters database should be developed. This will allow for improved model calibration, testing and application for developing recommendations to assist farmers.

7.3 References

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