Assessment of sorghum–cowpea intercrop system under water-limited conditions using a decision support tool

VGP Chimonyo[1]*, AT Modi[1] and T Mabhaudhi[1]
[1]*Crop Science, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, P. Bag X01, Scottsville 3209, Pietermaritzburg, South Africa*

ABSTRACT

Intercropping can improve crop productivity through increased water use efficiency (WUE). However, limited information exists to support its adoption and subsequent management. In such instances, crop models can be used as decision support tools to complement data from field trials. The Agricultural Production Systems Simulator Model (APSIM) was used to develop best management practices for improved yield and WUE for a sorghum–cowpea intercrop system for 5 sites in KwaZulu-Natal, South Africa: Richards Bay, Umbumbulu, Deepdale, Wartburg and Ukulinga. Each site represented 1 of 5 different bio-resource units. Planting dates (trigger season climate method, modelling and fixed date approaches), fertilizer rates (0, 50 and 100% recommended N rate), plant population (50% less and 50% more, for either sorghum or cowpea) and irrigation (deficit irrigation and rainfall-based approaches) were considered. In Deepdale, planting dates generated by the model gave high (952.2±85 and 326.3±68 kg·ha^{-1}) and stable yields for sorghum and cowpea, respectively. Adding 100% fertilizer improved both yield and WUE of the intercrop by 18.5 and 5.1%, respectively, in Umbumbulu and Wartburg. Across all environments, sorghum and cowpea plant populations of 39 000 and 13 000 plants·ha^{-1}, respectively, increased yield (26.11%) and WUE (15.54%) of the intercrop system. Deficit irrigation was more effective resulting in yield (12.84%) and WUE (11.09%) improvements. It is concluded that APSIM can be used to develop best management practices to assist in developing guidelines for improving productivity of intercrop systems under water-scarce conditions.

Keywords: best management practices, yield, water use efficiency

INTRODUCTION

Despite moderate progress in yield improvements, crop productivity in rainfed rural agricultural systems remains low and cannot provide food security for current and future demands (Dile et al., 2013; Vanlauwe et al., 2014). Besides socio-economic and bio-physical conditions, it has been observed that climate change and variability has resulted in a shift and change in duration of growing seasons, and increased incidences of seasonal dry spells and drought (Rosegrant et al., 2014). This has directly reduced agricultural water resources with an increase in water-scarce areas, and with formerly water-scarce regions becoming water stressed (Schilling et al., 2012). Given this scenario, farmers may not be equipped with the necessary risk management skills to adapt to the effects of climate change and variability (Venkateswarlu and Shanker, 2009). This is highlighted by continued water stress–related production losses. Researchers have, therefore, been tasked with coming up with relevant, innovative and practical adaptation strategies that are sustainable and resilient under water scarcity and stress.

There is renewed focus on restoration of sustainable and productive farming systems that are modelled on natural ecosystems (Mbow et al., 2014), and that can produce more from available water – 'more crop per drop' (Molden et al., 2010). As it stands, research has shown that intercropping has the potential to improve overall productivity through efficient and complementary use of water (Kour et al., 2013). The practice of intercropping is not new, but its advantages have not been fully exploited by rural farmers as a means to improve productivity, especially under water-limited conditions (Ouda et al., 2007). According to Chimonyo et al. (2015), this could be attributed to poor management options.

Decision making is core in farm management and has been the focus of numerous studies dealing with risk aversion and adaptation in resource-limited rainfed farming systems (Jat and Satyanarayana, 2013; Lehmann et al., 2013; Mbow et al., 2014). According to Graeff et al. (2012), information to guide best management practices is widely available. However, the challenge for a farmer is to determine how to use the information with respect to the type of management decisions to be made and the current risk. Therefore, farmers need an efficient, relevant and accurate way to evaluate data for specific management decisions. To improve farmers' capacity to make the best management decisions, robust management tools such as crop simulation models (CSM) are now being employed to generate quick and relevant information to aid in decision making.

Crop simulation models are computerised mathematical representations of crop growth, development and production, as a function of weather and soil conditions, and management practices that can reliably determine 'what if' and 'when' scenarios across diverse cropping system. Crop simulation models like APSIM (McCown et al., 1996) can assist in determining best management options at an operational and tactical level in response to low water availability. The objective of the study was, therefore, to apply a well-calibrated version of APSIM for a sorghum–cowpea intercrop to assess different management scenarios for selected areas in KwaZulu-Natal and thereby to define best management practices. Secondary to this, the model was used to identify best management practices to improve water use efficiency for sorghum–cowpea intercrop systems. The latter was achieved through scenario analyses based on a 10-year simulation period.

---

* To whom all correspondence should be addressed.
☎ +27 33 260 5447; Fax: +27 33 260 6094; e-mail: vimbayic@gmail.com
Received: 5 October 2015; accepted in revised form 17 March 2016

http://dx.doi.org/10.4314/wsa.v42i2.15
Available on website http://www.wrc.org.za
ISSN 1816-7950 (On-line) = Water SA Vol. 42 No. 2 April 2016

MATERIAL AND METHODS

Description of selected environments

KwaZulu-Natal, South Africa, has a diverse agro-ecological zone with 590 bio-resource units (BRUs) (Camp, 1999). Five sites located in five different BRUs in KwaZulu-Natal (Deepdale, Richards Bay, Umbumbulu, Ukulinga and Wartburg) were used in this analysis (Table 1). Richards Bay was considered as a low potential environment even though there is high annual rainfall (820–1 423 mm; Table 1). The location is characterised by sandy soils which are generally considered as having low agricultural potential. Ukulinga and Deepdale were considered as moderate potential environments based on the annual rainfall received of 650–850 mm (Table 1). Umbumbulu and Wartburg were considered as high potential environments since they received high annual rainfall (800–1 200 mm) and have clayey soils. In contrast to sandy soils, clayey soils retain more water and nutrients (Table 1).

Model calibration and testing

The calibration and testing of the APSIM were carried out using data obtained from field experiments conducted during the 2013/14 and 2014/15 growing seasons of a sorghum–cowpea intercrop established at the University of KwaZulu-Natal's Ukulinga Research Farm. Sub-plots comprised intercrop combinations, that is, sole sorghum, sole cowpea and sorghum–cowpea. For details of field experimental output refer to Chimonyo et al. (2016). During model testing, the APSIM was able to simulate growth, yield, water use and water use efficiency of sorghum–cowpea across different water regimes. Slight differences were observed between observed and simulated results for sorghum–cowpea intercrop system for biomass accumulation (2.1%), water use (2.6%) and water use efficiency (4.6%).

Simulation

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

Climate

For each site, 10-year (2004–2013) weather data that contained daily estimates of rainfall, minimum and maximum temperatures, solar radiation and reference evapotranspiration were sourced from the SASRI weather site (SASRI, 2015) using the nearest station to the location, except for Ukulinga where there was a weather station on site (Table 1). Average ambient temperature (TAV) and the annual amplitude in monthly temperature (AMP) were calculated using long-term daily minimum and maximum temperatures. The calculated values of TAV and AMP were inserted in the met files by the software program named 'tav_amp'.

Soil

The soil modules in APSIM are based on the international and African classification format. The APSIM soil module required soil properties such as bulk density (BD), total porosity, saturation (SAT), drained upper limit (DUL), crop lower limit (LL), plant available water capacity (PAWC) and pH to simulate yields and soil water related processes.

For each agro-ecological zone, available soil information was matched to pre-existing soils in the APSIM soil module. Soils at Ukulinga were described as shallow clayey to clayey loam with medium fertility (Mabhaudhi et al., 2013), which was matched with Clay_Shallow_MF_101mm (Table 2) in the APSIM soil file. Soils from Richards Bay were described as relatively deep and sandy with low fertility (Motsa et al., 2015), and were matched to Sandy_Medium_LF_111 mm (Table 3) in the APSIM soil file. Soils in Umbumbulu and Deepdale were similar and were described as relatively deep and clayey with medium fertility (Motsa, 2015; Table 4), and were matched with Clay_Medium_MF_171 mm in the APSIM soil file. Soils in Wartburg were described as relatively deep and clay loam–loamy with medium fertility (Chibarabada, 2015; Table 5), and were matched with Loam_Medium_MF_125mm in the APSIM soil file.

TABLE 1
Climate and soil description of sites to be included in the simulation

	Deepdale*	**Richards Bay***	**Umbumbulu***	**Ukulinga****	**Wartburg****
Geographical location	**28°01′S; 28°99′E**	**28°19′S; 32°06E**	**29°98′S; 30°70′E**	**29°37′S; 30°16′E**	**29°42′ S; 30°57′ E**
Altitude (m asl)	998	30	632	775	880
Bio-resource unit	Coast hinterland thornveld	Moist coast forest, thorn and palmveld	Dry coast hinterland and ngongoni veld	Coast hinterland thornveld	Moist midlands mistbelt
Annual rainfall	750–850 mm	820–1 423 mm	800–1 160 mm	644–838 mm	900–1 200 mm
Average temperature	18.4°C	22°C	17.9°C	18.4°C	20°C
Frost occurrence	Moderate	None	Light and occasional	Moderate occasional	Light and occasional
Soil texture class	Clay	Sand	Clay	Clay	Clay loam
Clay content	53%	< 5%	> 60%	< 29%	< 33%
Soil type	Jonkersberg (Jb)	Inhoek (Ik)	Hutton (Hu)	Chromic luvisols	Chromic luvisols
Field capacity (%)	45.22	10.91	45.13	46.32	39.36
Permanent wilting point (%)	34.71	6.22	34.53	23.03	23.36
Saturation (%)	50.36	47.11	51.20	46.73	50.36

*Adapted from *Motsa et al. (2015) and **Modi et al. (2014)*

TABLE 2
Properties of the African (generic) soil series available in APSIM's soil module which best describe soil water properties in Ukulinga (the effective root zone for crops was considered to be 0–60 cm)

Depth (cm)	Bulk density (g·cm^{-3})	Air dry[1] (mm·mm^{-1})	LL15[2] (mm·mm^{-1})	DUL[3] (mm·mm^{-1})	SAT[4] (mm·mm^{-1})
0–10	1.200	0.210	0.210	0.390	0.440
10–30	1.200	0.230	0.230	0.410	0.467
30–60	1.200	0.260	0.260	0.415	0.467

[1] *Air dry – hygroscopic soil water content*
[2] *Crop lower limit (LL15) – Permanent wilting point (PWP); lower limit of the available soil water range and a point when plants have removed all of the available water from a given soil, wilt and will not recover*
[3] *Drained upper limit (DUL) – field capacity (FC); amount of water remaining in a soil after the soil has been saturated and allowed to drain for approx. 24 h*
[4] *Saturation (SAT) – all pores in a soil are filled with water*

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

Depth (cm)	Bulk density (g·cm^{-3})	Air dry[1] (mm·mm^{-1})	LL15[2] (mm·mm^{-1})	DUL[3] (mm·mm^{-1})	SAT[4] (mm·mm^{-1})
0–10	1.600	0.060	0.060	0.165	0.360
10–30	1.600	0.070	0.070	0.170	0.365
30–60	1.600	0.090	0.090	0.172	0.370
60–90	1.600	0.110	0.110	0.175	0.370
90–120	1.600	0.130	0.130	0.180	0.370

[1, 2, 3, 4] *Refer to Table 2 footnote for descriptions*

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

Depth (cm)	Bulk density (g·cm^{-3})	Air dry[1] (mm·mm^{-1})	LL15[2] (mm·mm^{-1})	DUL[3] (mm·mm^{-1})	SAT[4] (mm·mm^{-1})
0–10	1.200	0.210	0.210	0.390	0.440
10–30	1.200	0.230	0.230	0.410	0.467
30–60	1.200	0.260	0.260	0.415	0.467
60–90	1.200	0.290	0.290	0.420	0.470
90–120	1.200	0.320	0.320	0.425	0.475

[1, 2, 3, 4] *Refer to Table 2 footnote for descriptions*

TABLE 5
Properties of the African (generic) soil series available in APSIM's soil module which best describe soil water properties in Wartburg (the effective root zone for crops was considered to be 0–120 cm)

Depth (cm)	Bulk density (g·cm^{-3})	Air dry[1] (mm·mm^{-1})	LL15[2] (mm·mm^{-1})	DUL[3] (mm·mm^{-1})	SAT[4] (mm·mm^{-1})
0–10	1.400	0.170	0.170	0.301	0.400
10–30	1.400	0.180	0.180	0.310	0.410
30–60	1.400	0.190	0.190	0.310	0.420
60–90	1.400	0.215	0.215	0.315	0.430
90–120	1.400	0.250	0.250	0.317	0.440

[1, 2, 3, 4] *Refer to Table 2 footnote for description.*

Scenario analyses

Four management options were used to develop scenarios used as a guide for recommending best management practices in KwaZulu-Natal. The scenarios were:

Scenario 1: Planting dates

Three approaches (trigger season climate method, modelling and fixed date approaches) were used to establish the planting dates. The trigger season method is used to determine the onset and length of a growing season from long-term weather data and thus can be used to determine planting dates (Hartkamp et al., 2001). For this method, the onset of the season is assumed to be when the ratio of sum total of monthly rainfall and reference evapotranspiration (ET_o) becomes greater than 0.5.

$$\frac{\text{Rainfall}}{\text{Reference evapotranspiration}} \geq 0.5 \qquad (1)$$

By plotting long-term monthly averages of rainfall, ET_o and 0.5 ET_o, the onset of a growing season can be determined by observing where rainfall exceeds 0.5 ET_o.

$$\text{Rainfall} \geq 0.5 \text{ reference evapotranspiration} \qquad (2)$$

An advantage to this approach is that it is site specific if weather data are available. On the other hand, a major limitation towards practical application of this method would be that farmers and extension service providers may not always have access to long-term weather data, specifically ET_o, from weather stations. For this exercise, planting dates, as defined by the onset of the growing season, were established based on 10-year monthly averages of rainfall, ET_o and 0.5 ET_o. For Ukulinga, Deepdale and Richardss Bay, trigger season occurred on 1 October while it occurred on 1 and 15 September for Umbumbulu and Wartburg, respectively (Fig. 1).

The current planting dates in use by farmers are those recommended by agricultural agencies and extension service providers (Van Averbeke, 2002). These tend to be broad and do not accommodate large variation in agro-ecologies and their constantly shifting boundaries within sub-Saharan Africa As it is, South Africa exhibits a wide variation of BRUs. Due to climate change and variability this variation has increased and there is an observed increase in land under semi-arid and arid regions since 2000 (Cairns et al., 2013). There was need to redefine planting dates, in terms of fixed dates, as this approach is much easier for farmers to work with. Five planting dates, 15 September, 15 October, 15 November, 15 December and 15 January were then used for the simulation representing early to late planting.

As a management tool, most CSMs are able to generate planting dates from climate and soil data. This is done based on predefined criteria that take into account amount of rainfall, days taken to achieve that quantity, and soil water content within the seedling zone. The main advantage of using CSMs is that they are fast and reliable. They can also be site-specific, thus improving the accuracy of recommendations, or scaled up to give general assessment on a regional scale. For each site, APSIM was used to generate planting dates using a user-defined criterion of 'sum of rainfall in a 10-day period where at least a cumulative amount of 20 mm is received' (Raes et al., 2004). In addition, a fixed soil water content of 80% of field capacity of the top 15 cm was considered. The criteria set reflected planting conditions often used by farmers in semi-arid regions where planting is often done after the onset of the rainy season. Across the years, frequencies of planting dates falling in similar months were observed and mean planting date for that month was calculated. For evaluating crop yield and WUE, planting dates with the highest frequency of appearance within the 10-year weather data set were used for scenario analysis (Table 6).

TABLE 6
Model generated planting dates for the agro-ecological zones (Wartburg, Deepdale, Richards Bay, Umbumbulu, and Ukulinga) used in this study

Site	Mean planting date (Julian day)	Frequency (out of 10 years)	Standard deviation (+/-)[1]
Wartburg	21 January	10	8.12
Umbumbulu	16 January	7	7.00
Ukulinga	15 January	6	7.18
Richards Bay	18 November	10	5.7
Deepdale	21 November	6	5.1

[1] *Standard deviation (days) of mean planting date generated by the model*

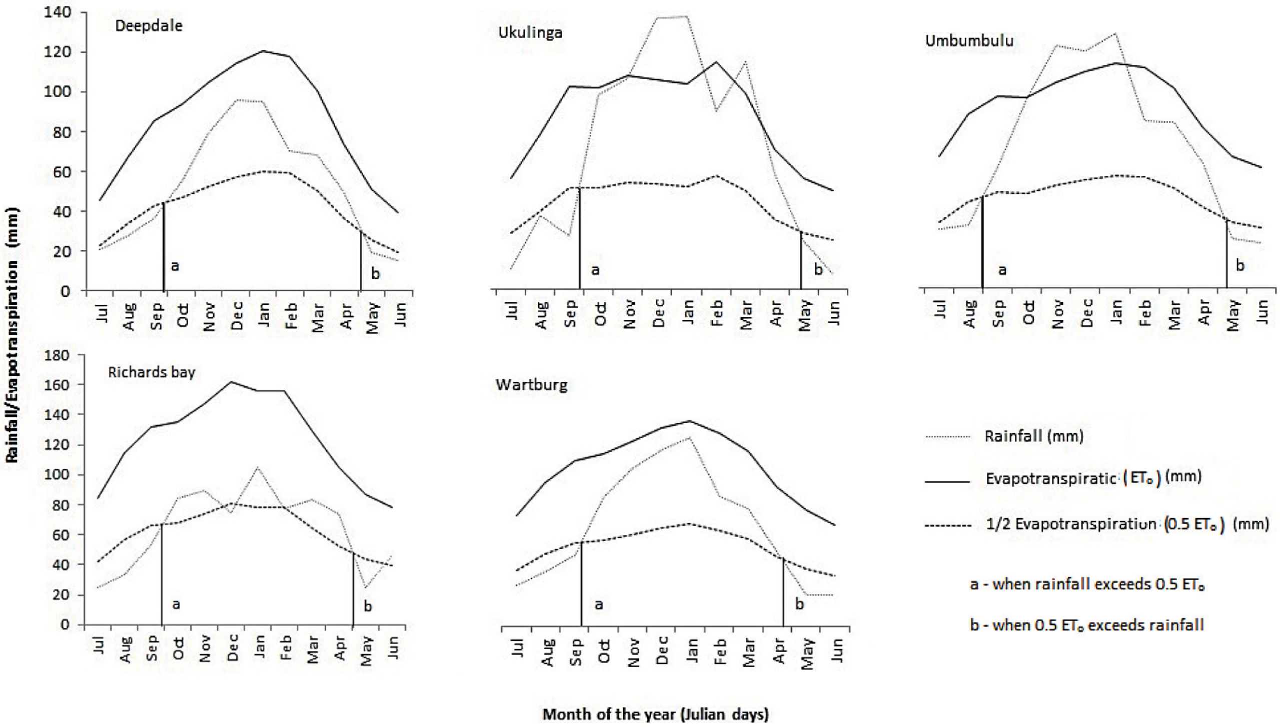

Figure 1

Determination of start and end of growing season for Deepdale, Richards Bay, Umbumbulu, Ukulinga and Wartburg using monthly average data over 10 years (2004–2013) for rainfall, reference evapotranspiration (ETo) and 0.5 ETo. The onset of a growing season (a) is when rainfall exceeds 0.5 ETo. The period between a and b, is the length of the growing season. The end of the growing season (b) is marked by the decline of the rainfall to values below 0.5 ETo.

Scenario 2: Fertilizer application rates and time of application

Sorghum requires about 85 kg·ha^{-1} N to achieve a tonnage of 2 – 3.5 t·ha^{-1} (Wylie, 2004). Sorghum grain yields in SSA are approx. 900 kg·ha^{-1} on average, compared to the world average of 1 500 kg·ha^{-1} (Olembo et al., 2010). Increasing the yield to meet and/or surpass world averages would be desirable to improve access and availability of food. However, a major limiting factor is fertilizer use and accurate recommendations (Bationo, 2007). Based on recommendations by Wylie (2004), fertilizer levels representative of 0, 50 and 100% of the recommended N for optimum sorghum production were used for model scenario analyses. The range provided a scenario whereby farmers do not have access to fertilizers (0%), have some fertilizer (50%) or have 100% of the recommended N requirements.

Scenario 3: Plant populations

To determine the optimum plant population for the component crops for each site, simulations were performed using plant populations that were 50% less and 50% more than the recommended plant population. Under semi-arid conditions, a plant population of 26 666 plants·ha^{-1} is recommended for sorghum (du Plessis, 2008). For cowpea, an optimum plant population of 13 000 plants·ha^{-1} was used. These have been observed to give the best productivity in terms of land equivalent ratio of intercrop systems (Oseni, 2010). Simulations were carried out by maintaining the recommended plant population of one component and changing the other resulting in a total number of 10 simulations:

- Sorghum with a fixed population of 26 000 plants·ha^{-1} intercropped with cowpea with populations of 6 500 (A1), and 19 500 (A2) plants·ha^{-1}
- Sorghum with varying populations of 13 000 (B1), and 39 000 (B2) plants·ha^{-1} intercropped with cowpea with a fixed population of 13 000 plants·ha^{-1}
- The baseline population (C1) used to compare changes in yield and WUE was a sorghum and cowpea plant population of 26 000 and 13 000 plants·ha^{-1}, respectively.

Scenario 4: Irrigation

To reduce the yield gap that often occurs in rainfed farming systems due to water stress, supplementary irrigation was included as a management option. Two approaches were used, namely, deficit irrigation and rainfall-based approaches. Deficit irrigation (DI) is a method whereby irrigation is applied below full crop water requirement in such a way that there is little yield reduction and water is saved (Upchurch et al., 2005). Types of DI include (i) withholding irrigation until a predefined allowable soil water depletion of plant available water (PAW) before refilling the soil back to a predefined PAW, (ii) PAW is maintained at a predetermined level below full crop water requirement, and (iii) irrigation is only applied at full crop water requirements at critical growth stages (Fereres and Soriano, 2006). For this scenario, the first method for DI was used and allowable soil water depletion of 40% of PAW was defined before irrigation refilled it back to 80% of PAW. This ensured that soil water content never reached levels that could cause water or aeration stress to the plant.

In semi-arid conditions, rainfall distribution is an important factor affecting crop productivity. To manage this, supplementary irrigation during periods of low or no rainfall can reduce crop water stress and improve productivity. Irrigation scheduling was based on weekly rainfall where the conditions were that if rainfall received over 7 days was less than recorded ET$_o$ for the same period, the difference would be applied as supplementary irrigation. This ensured that crop water requirement was met and that the crop did not suffer from water stress.

Data analyses and evaluation

Within the model, WU was determined as the sum of crop water uptake from the whole profile (sorghum Ep + cowpea Ep) and soil evaporation (Es). Each scenario was run independently from the other to minimise interactive effects of the scenarios. Since APSIM does not calculate WUE directly, simulated outputs (WU, yield and biomass) were used to determine WUE as follows:

$$\text{WUEy} = \frac{Y}{\text{WU}} \tag{3}$$

where: WUEy = water use efficiency (kg·mm^{-1}·ha^{-1}), Y = total grain yield (sorghum + cowpea) (kg·ha^{-1}), and WU = the crop water use (WU) (mm).

Descriptive statistics such as means, standard deviations, and box-and-whisker plots were used to analyse outputs. Box-and-whisker plots can show stability and general distribution of the sets of data.

RESULTS AND DISCUSSION

Scenario 1: Planting dates

Different scenarios for planting dates gave different mean yields and mean yield distribution for sorghum and cowpea across the five environments over the simulated years. Based on the observed results, simulated average yields for sorghum at Richards Bay, Umbumbulu, Deepdale, Wartburg and Ukulinga were 952.7 (±185.42), 987.5 (±149.37), 820.5 (±122.99), 879.6 (±231.97) and 935.8 kg·ha^{-1} (±122.19), respectively. Yield averages for cowpea were 281.0 (±86.39), 355.9 (±153.24), 139.6 (±55.69), 260.1 (±153.36) and 321.7 kg·ha^{-1} (±110.58), respectively. Low yields observed for Deepdale for both sorghum and cowpeas could be due to the overall low rainfall at this site (see Appendix 1), while high yields observed for Umbumbulu, Richards Bay and Ukulinga were attributed to high rainfall received at these sites. Observed yields of sorghum were consistent with regional yield averages of 900 kg·ha^{-1} (Olembo et al., 2010). On the other hand, yields of cowpea were lower than those found by Ajeigbe et al. (2010) and Oseni (2010) who obtained yields between 400 and 900 kg·ha^{-1} under sorghum–cowpea intercropping. It should be noted that the differences in cowpea yield could be attributed to plant populations that were higher relative to current simulation studies. This would suggest that yields of cowpea within the intercrop system are influenced by population density.

The ideal planting date is a scenario where overall yields are high and there is less variation over time (Kucharik, 2008). The ideal planting date for sorghum and cowpea at Richards Bay was that which was generated by the model (18 Novermber) and this yielded an average of 1 050.7 kg·ha^{-1} (±45.57) for sorghum and 355.6 kg·ha^{-1} (±50.57) for cowpea. Similarly, the model generated planting date for Deepdale (21 November) and Ukulinga (15 January) simulated high yields for both sorghum

(959.8±88.81 kg·ha^{-1} and 995.9±87.81 kg·ha^{-1}, respectively) and cowpea (160.6±38.57 kg·ha^{-1} and 156.5±42.63 kg·ha^{-1}, respectively) (Fig. 2). For Umbumbulu, and Wartburg planting dates that gave high and stable yields for sorghum (970.8±106.32 kg·ha^{-1} and 1 037.2±68.78 kg·ha^{-1}, respectively) were observed by using a fixed planting date (15 October). The fixed planting dates did not always give high yields for cowpea, but results show yield stability as indicated by low standard deviations relative to other planting dates (426.2±134.94 kg·ha^{-1}, 332.8±115.08 kg·ha^{-1}, 347.4±97.76 kg·ha^{-1}, respectively).

Sandy soils at Richards Bay are characterized as having low water-holding capacity due to large pore spaces between soil particles, such that water easily succumbs to drainage. Sandy soils require frequent wetting intervals so as to maintain desired soil water content (SWC) for seed germination, especially at the root zone. On the other hand, clayey soils like those at Deepdale require high amounts of rainfall to make water available for plants. Therefore, low rainfall during the early months of the official growing season may not be adequate for desired SWC at planting.

For low potential environments like Richards bay and Deepdale, using model-generated planting dates can avoid false starts to planting, that is, planting dates that do not have all the requirements for ideal planting conditions. Fixed planting dates for Umbumbulu, Ukulinga and Wartburg were within the official planting window (15 Oct–15 Dec) for sorghum across the KwaZulu-Natal region (ARC, 2010). During this period rainfall amount was observed to be high with an average of 95 mm·month^{-1} (see Appendix 1, Table A1) and evenly distributed. SWC is sufficient for seed germination and thereafter to sustain growth of developing seedings.

In low rainfall areas (Deepdale and Wartburg), an early planting date (15 September) improved WUE (8.29% and 14.52%, respectively) for the intercrop system relative to planting dates that produced high yield. Under low-rainfall conditions it could be that temporal use of radiation by the cropping system was increased resulting in an increase in biomass production and yield. Conversely, in high-rainfall areas (Ukulinga, Richards Bay and Umbumbulu), late planting dates (15 January) resulted in improvements of WUE (19.11%, 15.15% and 10.82%, respectively) relative to planting dates where high yields were observed. Improvements in WUE in high-rainfall environments was associated with low water use while yield remained unchanged (Table 7). Based on the model output, less water was lost through unproductive means (soil evaporation, runoff and drainage) relative to planting dates where high yields were observed. Although late planting was observed to improve WUE based on rainfall received during the growth period, including the whole season's rainfall in the calculation substantially reduced WUE. To increase temporal use of water, double cropping with early maturing cultivars of sorghum and cowpea can be employed. In the context of the sorghum–cowpea intercrop system, double cropping would be growing the cropping system twice in the same season in a relay manner.

Scenario 2: Fertilizer application rate

Long-term simulation showed that overall yields were improved with the use of fertilizer (Table 8). The observed results were attributed more to an increase in sorghum yields than cowpea yields. Overall, adding 85 kg·ha^{-1} N had a more positive effect (12.7%) on sorghum yield than when 42.5 kg·ha^{-1} N was applied (5.7%). Results of simulations show that sorghum yields at Wartburg, Umbumbulu and Ukulinga were more responsive to fertilizer application (Table 8) when compared to Richards Bay and Deepdale. This was attributed to high rainfall

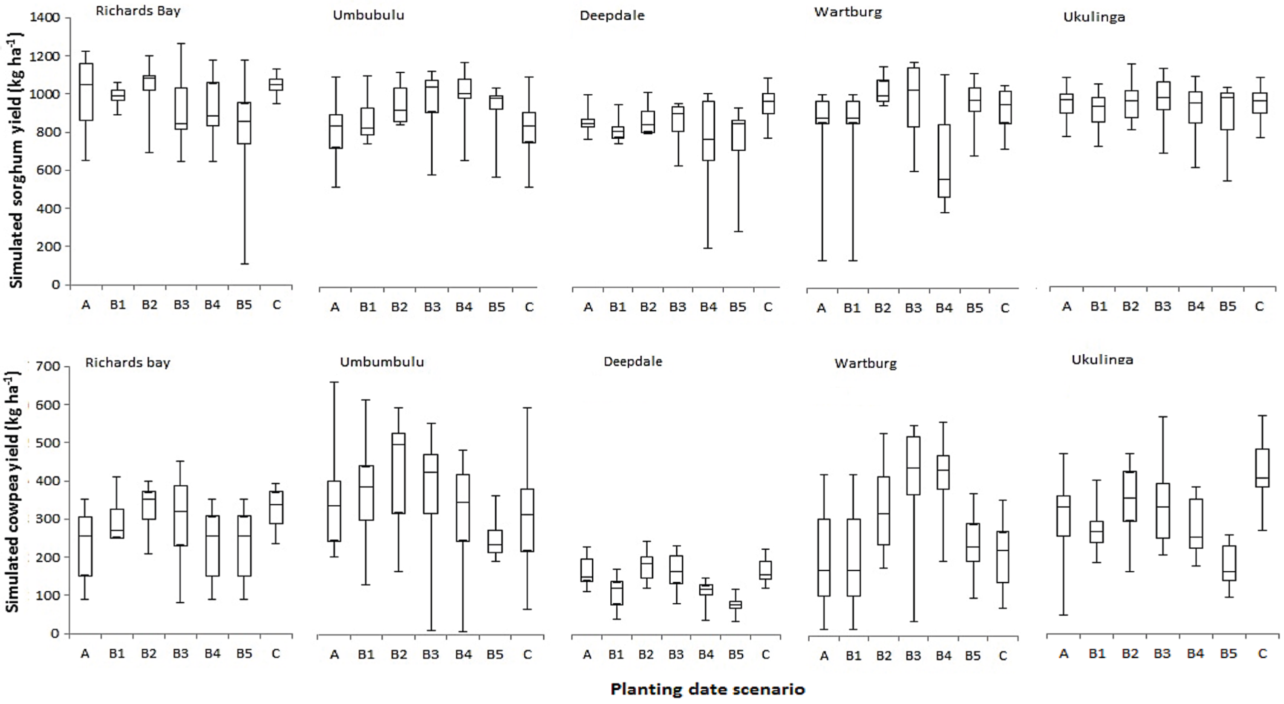

Figure 2

Simulated yield response of sorghum–cowpea intercrop system across the five environments (Richards Bay, Umbumbulu, Deepdale, Wartburg and Ukulinga) for different planting date scenarios. A: site-specific planting date defined by trigger season method. B1–5: fixed planting dates starting from (B1) 15 Sept, (B2) 15 Oct, (B3) 15 Nov, (B4) 15 Dec, (B5) 15 Jan, respectively. C: planting dates generated by APSIM.

amounts received at Wartburg, Umbumbulu and Ukulinga. The observed low responses to fertilization at Richards Bay and Deepdale were due to the fact that plants absorb less nitrogen when soil water content is low. Adding high levels of fertilizer at Deepdale without improving water availability would not necessarily improve yields but rather could reduce the system's N use efficiency. On the other hand, the low improvements in sorghum yield in Richards Bay could be attributed to leaching during rainfall events. Richards Bay is characterised by sandy soils which are generally associated with leaching. To improve fertilizer response of sorghum in environments with sandy soils, split applications and timing of application to coincide with specific growth stages should be considered.

Overall, adding 85 kg·ha^{-1} N had a more positive (5.08%) effect on WUE for the intercrop system than when 42.5 kg·ha^{-1} N was applied (3.43%). Improvements in WUE could have been attributed to increase in yield in response to fertilizer application. Improving soil fertility improves water use by increasing photosynthetic capacity of the leaf through improved enzyme function and enhanced carbon dioxide assimilation (Deng et al., 2006). Observed results for the interaction between WUE and N fertilizer agree with results by Gan et al. (2010), who observed an improvement in WUE with additions of different rates of N fertilizer. Under rainfed cropping systems application of fertilizer should always be considered as it has been observed to improve WUE.

Scenario 3: Plant populations

Results of plant population scenarios showed that different plant combinations resulted in different crop yield responses for both sorghum and cowpea. In general, changing the plant population of cowpea did not have a pronounced effect on sorghum (952.63±125.36 kg·ha^{-1}). It could be that cowpea did not compete with sorghum for resources such as radiation and water, and would suggest that the plant population of cowpea can still be

TABLE 7
Comparison of simulated sorghum and cowpea yield, water losses, total water used (WU) and water use efficiency (WUE) in response to different environments and planting dates

Environment	Planting date	Sorghum yield (kg·ha^{-1})	Cowpea yield (kg·ha^{-1})	Rainfall[1] (mm)	Water lost[2] (mm)	Cowpea water uptake[3] (mm)	Sorghum water uptake[4] (mm)	WU[5] (mm)	WUE[6] (kg·ha^{-1}·mm^{-1})	WUE impr[7] (%)
Richards Bay	15 Jan	983.6	296.4	278.22	232.66	31.97	27.15	291.79	4.42	15.15
Umbumbulu	16 Jan	951.1	251.7	314.14	286.26	33.98	21.68	343.11	3.56	10.82
Deepdale	15 Sep	811.5	104.0	246.57	199.47	23.15	32.08	254.71	3.86	8.29
Wartburg	15 Sep	928.2	249.9	259.91	229.15	38.44	25.03	322.62	3.91	14.52
Ukulinga	15 Jan	904.7	196.0	309.17	276.57	29.84	23.58	330.00	3.51	19.11

[1] *10-year average rainfall received during the growing period*
[2] *Water lost through unproductive ways such as runoff, drainage and soil evaporation*
[3] *Water taken up and transpired by cowpea*
[4] *Water taken up and transpired by sorghum*
[5] *Amount of water used through productive (crop water uptake) and unproductive means (runoff, drainage and soil evaporation)*
[6] *Ratio of yield (kg-ha^{-1}) or crop output per water used to produce the yield*
[7] *WUE improvements relative to WUE obtained from ideal planting dates (21 Nov, 18 Nov, 15 Oct, 15 Oct and 15 Nov for Richards Bay, Umbumbulu, Deepdale, Wartburg and Ukulinga, respectively)*

TABLE 8
Simulation of yield, water use and water use efficiency and percentage improvements for yield and water use efficiency of sorghum-cowpea intercrop system in response to fertilizer

Fertilizer	Environment	Sorghum (kg·ha^{-1})	Cowpea (kg·ha^{-1})	Water use (mm)	WUE[1] (kg·ha^{-1}·mm^{-1})	Yield impr[2] (%)	WUE impr[3] (%)
42.5 kg·ha^{-1} N	Umbumbulu	1 002.3	296.9	301.79	4.64	5.12	5.14
	Ukulinga	915.4	197.5	363.11	3.06	4.56	0.62
	Richards Bay	952.5	232.6	259.71	4.63	5.13	4.92
	Deepdale	923.5	104.3	312.86	3.28	2.97	2.33
	Wartburg	1 023.9	249.4	331.90	3.96	7.91	3.73
85 kg·ha^{-1} N	Umbumbulu	1 060.3	295.3	306.79	4.69	12.51	6.97
	Ukulinga	988.7	196.8	360.11	3.29	15.65	2.74
	Richards Bay	1 006.7	295.4	253.71	4.71	7.63	3.52
	Deepdale	992.4	103.2	312.86	3.50	3.23	4.26
	Wartburg	1 126.82	238.96	321.76	4.24	23.12	7.91

1 Water use efficiency
2 Yield improvements relative to calculated yield simulated under 0 kg·ha^{-1} N
3 WUE improvements relative to calculated WUE simulated from simulated crop water use (crop water uptake unproductive, water loss due to soil evaporation, drainage and runoff) under 0 kg·ha^{-1} N

increased further. Conversely, cowpea yield was affected by the change in sorghum population (Fig. 3). For all the environments, reducing sorghum plant population improved cowpea yield by between 5.6 and 35.1%. Although increasing sorghum population increased its overall yield, results showed that this had a negative effect on simulated cowpea yield (12.63–16.38% reduction, Table 9). Sorghum was a stronger competitor for resources (radiation and water) than cowpea. Increasing the sorghum population might have increased the extinction coefficient of the top layer canopy and reduced the amount of solar radiation received by cowpea, the understorey. To improve yield of cowpea under high sorghum population, changing row orientations and arrangements can reduce competition for resources between sorghum and cowpea.

Under the B2 scenario (sorghum and cowpea plant populations of 39 000 and 13 000 plants·ha^{-1}, respectively), WUE was improved by an overall 10.39% relative to the baseline plant population. Improvements of WUE could be related to an increase in sorghum yield due to increased plant population. It was also observed that WU in Richards Bay (263.23±6.36 mm), Umbumbulu (336.56±8.51 mm), Deepdale (363.23±5.51 mm), Wartburg (353.23±4.61 mm), and Ukulinga (314.53±8.36 mm) was relative to corresponding WU of baseline populations across the sites (260.32, 339.25, 359.26, 352.30 and 310.25 mm). Increased yield output and unchanged WU thus resulted in an increase in WUE. Increasing plant population increases canopy size per unit area. This in turn increases water uptake and loss through transpiration, relative to that which would have been lost through soil evaporation. Under water scarcity, sorghum populations can be increased above the baseline population used in this study. However, this would not improve nutritional water productivity of the system. Maintaining sorghum populations and increasing cowpea populations could improve nutritional water productivity of sorghum–cowpea intercrop systems.

Scenario 4: Irrigation

Irrigation improved productivity and WUE of the sorghum–cowpea intercrop system (Table 10). Irrigating at weekly intervals based on rainfall analysis simulated higher yields (5.63%) relative to irrigation scheduling based on allowable soil water depletion (ASWD) across all the environments (Table 10). This could be because irrigation based on weekly rainfall events increased availability of water, reducing crops exposure to intermittent water stress. Across all environments, it was observed that irrigation had a large and positive effect on yield for both cowpea and sorghum at Richards Bay while the least effects were observed at Wartburg. Soils for Wartburg are clay-loam and, according to Kirkham (2005), clay-loam soils are good for irrigation since the clay component ensures good water-holding properties and the loam component good aeration and drainage. In contrast, soils at Richards Bay are deep and sandy and these soils are inherently well-drained and well-aerated, and have poor water-holding capacity. This often translates to significant drainage losses as opposed to the water being taken up by the plant. Conversely, the simulation results showed that water lost through unproductive means, namely drainage, was low. This could have been because rainfall was

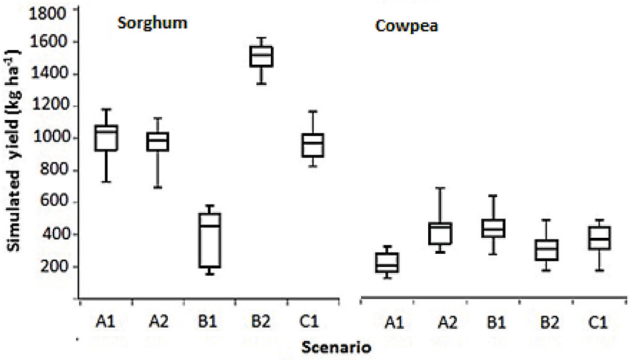

Figure 3

Simulated mean yield response of sorghum–cowpea intercrop system across the five environments (Richards Bay, Umbumbulu, Deepdale, Wartburg and Ukulinga) in response to different plant populations (A1 – sorghum 26 000 plants·ha^{-1} and cowpea 6 500 plants·ha^{-1}; A2 – sorghum 26 000 plants·ha^{-1} and cowpea 19 500 plants·ha^{-1}; B1 – sorghum 13 000 plants·ha^{-1} and cowpea 13 000 plants·ha^{-1}; B2 – sorghum 26 000 plants·ha^{-1} and cowpea 19 500 plants·ha^{-1} and C1 – sorghum 39 000 plants·ha^{-1} and cowpea 13 000 plants·ha^{-1})

TABLE 9
Comparison of simulated sorghum and cowpea yield, water losses, total water used (WU) and water use efficiency (WUE) in response to different environments and plant populations

Environment	Cowpea yield (kg·ha^{-1})	Sorghum yield (kg·ha^{-1})	Average rainfall (mm)	Water lost[1] (mm)	Cowpea water uptake[2] (mm)	Sorghum water uptake[3] (mm)	WU[4] (mm)	WUE[5] (kg·ha^{-1}·mm^{-1})	WUE impr.[6] (%)
Richards Bay	228.1	1 271.0	302.00	260.40	39.96	39.96	340.32	4.79	7.84
Umbumbulu	318.4	1 390.9	456.97	391.02	45.89	33.55	470.47	3.75	3.10
Deepdale	144.5	1 203.2	284.14	225.88	34.52	49.49	309.89	4.45	13.29
Wartburg	375.3	1 323.2	569.95	475.31	64.83	39.01	579.15	3.41	4.68
Ukulinga	1 453.8	360.3	421.03	322.92	37.83	37.83	404.78	4.61	23.81

1 Water lost through unproductive ways such as runoff, drainage and soil evaporation
2 Water taken up and transpired by cowpea
3 Water taken up and transpired by sorghum
4 Amount of water used through productive (crop water uptake) and unproductive means (runoff, drainage and soil evaporation)
5 Ratio of yield (kg-ha^{-1}) or crop output per water used to produce the yield
6 WUE improvements observed WUE relative to WUE obtained from baseline plant populations of 26 000 and 13 000 plants-ha^{-1} for sorghum and cowpea, respectively

TABLE 10
Comparison of simulated sorghum and cowpea yield, water losses, total water used and water use efficiency in response to different irrigation scenarios and environments

Irrigation scheduling	Environment	Cowpea yield (kg·ha^{-1})	Sorghum yield (kg·ha^{-1})	Average rainfall (mm)	Water lost^1 (mm)	Cowpea water uptake^2 (mm)	Sorghum water uptake^3 (mm)	Irrigation (mm)	Total water added (mm)	WU^4 (mm)	WUE^5 (kg·ha^{-1}·mm^{-1})
Soil water deficit	Umbumbulu	296.3	926.5	298.90	276.16	48.24	25.70	33.60	332.50	383.70	3.18
	Ukulinga	384.0	996.6	456.97	392.79	54.32	23.79	7.27	464.25	478.17	2.88
	Richards Bay	429.7	1209.3	284.14	244.09	35.39	49.85	36.36	320.50	365.69	4.48
	Deepdale	142.8	896.7	567.34	499.90	74.78	26.35	26.04	593.37	627.07	1.65
	Wartburg	406.9	1000.0	360.10	330.39	68.34	26.18	50.00	410.10	474.91	2.96
Rainfall	Umbumbulu	315.8	972.8	298.90	332.97	51.35	26.31	109.09	407.99	519.72	2.48
	Ukulinga	384.3	996.7	456.97	428.84	54.40	23.72	45.45	502.43	552.41	2.50
	R ichards Bay	429.3	1346.7	284.14	316.30	33.94	53.61	95.45	379.59	499.31	3.55
	Deepdale	143.7	935.6	567.34	673.60	74.72	27.09	200.97	768.31	976.38	1.10
	Wartburg	395.9	1009.3	360.10	371.23	64.94	26.39	64.00	424.10	526.56	2.66

1 Water lost through unproductive ways such as runoff, drainage and soil evaporation
2 Water taken up and transpired by cowpea
3 Water taken up and transpired by sorghum
4 Amount of water used through productive (crop water uptake) and unproductive means (runoff, drainage and soil evaporation)
5 Ratio of yield (kg·ha^{-1}) or crop output per water used to produce the yield

low but evenly distributed during the growth period. This meant that soil water was more available within the root zone and less was lost through unproductive means (Table 10). Scheduling irrigation based on weekly rainfall events can result in wasteful use of water by over-application of water relative to crop water requirements. This was quite evident with high amounts of water lost through unproductive means (Table 10).

Overall irrigation reduced WUE of the intercrop system relative to rainfed conditions. This could be attributed to high amounts of water lost through unproductive means under irrigation relative to rainfed conditions. This confirms early observations where, although yield improved, high amounts of water were lost through unproductive use. Conversely, results of WUE show that irrigating based on ASWD resulted in high (18.88%) WUE of the intercrop system relative to WIR. Similarly, the observed results could be attributed to large amount of applied water being lost through unproductive use. In this regard, ASWD can be suitable to improve yield of the intercrop system. However, to further increase WUE more irrigation water management options are required.

RECOMMENDATIONS FOR BEST MANAGEMENT PRACTICES

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

- To achieve high and sustainable yields, low potential environments similar to Deepdale and Wartburg (low annual rainfall) and Richards Bay (deep sandy soils) should plant intercrop of sorghum–cowpea around 15 November.
- Environments that receive high rainfall and are characterised by shallow clay soils like Ukulinga need to plant sorghum–cowpea intercrop system around 15 December. High rainfall areas with deep clay soils similar to Umbumbulu and Wartburg should plant on 15 October.
- To achieve high WUE, early planting (15 September) and late planting (15 January) in low-rainfall and high-rainfall areas, respectively, is recommended.
- Farmers in environments similar to Deepdale are recommended to add 42.5 kg·ha^{-1} N since adding high quantities fertilizer will not always improve yield and WUE.
- Fertilizer levels of 85 kg·ha^{-1} N are recommended for use in high-rainfall environments such as Ukulinga, Richards Bay and Wartburg.
- Across all the environments, and where increasing sorghum yield and overall WUE is most desired, the ideal plant population of sorghum should be 39 000 plants·ha^{-1} in combination with 13 000 plants·ha^{-1} of cowpea.
- When yields of both crop species are desired increasing cowpea plant population to 19 500 plants·ha^{-1} is recommended.
- For all the environments, weekly scheduling of irrigation based on weekly rainfall amount resulted in high yields. However, this also produced low WUE. It can be recommended that, for all environments, using soil water deficit is better since yield and WUE were higher relative to weekly scheduling of irrigation based on weekly rainfall amount.
- To improve yields under irrigation, weather forecast data should be made readily available for farmers so as to improve irrigation management options and WUE.
- Using a 10-year data period for scenario analyses gave a good start point for assessing the impacts of changes in management practices in an intercropping system. This is not, however, sufficient to reach strong and reliable conclusions (i.e., planting dates). Where available, climate data for 30 years or more should be used to assess the effect of climate on intercrop management options.
- The determination/calculation of planting dates based on available data (historical and forecast data) should be recommended to resource-poor farmers as it is affordable.

CONCLUSIONS

APSIM was efficient at assessing yield responses for sorghum–cowpea under different management scenarios for 5 rainfed agro-ecologies in KwaZulu-Natal. In addition, the model was able to identify best management practices for improved water use efficiency for sorghum–cowpea intercrops under rainfed conditions. For the environments included in this study, the sorghum–cowpea intercrop system was most responsive to changes in planting dates and plant populations while moderate changes were observed in response to fertilization and irrigation. Overall, the model can be used as a tool to develop best management options for increased yield and WUE for intercropping under water-scarce agro-ecologies. To improve the assessment of yield response for sorghum–cowpea intercrop to N fertilizer, site-specific N recommendations should be used in scenario analyses. There is still need to apply APSIM to assess the effects of the combinations of these management options on yield and WUE for sorghum–cowpea intercrop systems.

ACKNOWLEDGEMENTS

The Water Research Commission of South Africa is acknowledged for initiating, funding and directing the study through WRC Project No. K5/2274//4 'Determining water use of indigenous grain and legume food crops' (WRC, 2014).

REFERENCES

AJEIGBE HA, SINGH BB, ADEOSUN JO and EZEAKU IE (2010) Participatory on-farm evaluation of improved legume-cereals cropping systems for crop-livestock farmers: maize-double cowpea in Northern Guinea Savanna Zone of Nigeria. *Afr. J. Agric. Res.* **5** 2080–2088.

ARC (AGRICULTURAL RESEARCH COUNCIL, SOUTH AFRICA) (ARC) (2010) Sorghum production guidelines. ARC Directorate Plant Production, Pretoria, South Africa.

BATIONO A, WASWA B, KIHARA J and KIM TU J (2007) *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities*. Springer Science & Business Media. Springer, the Netherlands. http://dx.doi.org/10.1007/978-1-4020-5760-1

CAIRNS JE, HELLIN J, SONDER K, ARAUS JL, MACROBERT JF, THIERFELDER C and PRASANNA BM (2013) Adapting maize production to climate change in sub-Saharan *Africa. Food Secur.* **5** 345–360. http://dx.doi.org/10.1007/s12571-013-0256-x

CHIBARABADA TP (2014) Seed quality and water use characteristics of a Bambara groundnut (*Vigna subterranea* L) landrace differing in seed coat colour. MSc thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

CHIMONYO VGP, MODI AT and MABHAUDHI T (2015) Perspective on crop modelling in the management of intercropping systems. *Arch. Agron. Soil Sci.* **61** 1–19. http://dx.doi.org/10.1080/03650340.2015.1017816

CHIMONYO VGP, MODI AT and MABHAUDHI T (2016) Water use and productivity of a sorghum–cowpea–bottle gourd intercrop system. *Agric. Water Manage.* **165** 82–96. http://dx.doi.org/10.1016/j.agwat.2015.11.014

COOPER PJM, DIMES J, RAO KPC, SHAPIRO B, SHIFERAW B and TWOMLOW S (2008) Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agric. Ecosyst. Environ.* **126** 24–35. http://dx.doi.org/10.1016/j.agee.2008.01.007

DENG X-PX, SHAN L, ZHANG H and TURNER NCN (2006) Improving agricultural water use efficiency in arid and semiarid areas of China. *Agric. Water. Manage.* **80** 23–40. http://dx.doi.org/10.1016/j.agwat.2005.07.021

DILE YT, KARLBERG L, TEMESGEN M and ROCKSTRÖM J (2013) The role of water harvesting to achieve sustainable agricultural intensification and resilience against water related shocks in sub-Saharan Africa. *Agric. Ecosyst. Environ.* **181** 69–79. http://dx.doi.org/10.1016/j.agee.2013.09.014

FERERES E and SORIANO MA (2006) Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.* **58** 147–159. http://dx.doi.org/10.1093/jxb/erl165

FLORA CB (2010) Food security in the context of energy and resource depletion: Sustainable agriculture in developing countries. *Renew. Agric. Food Syst.* **25** 118–128. http://dx.doi.org/10.1017/s1742170510000177

GAN YT, WARKENTIN TD, BING DJ, STEVENSON FC and MCDONALD CL (2010) Chickpea water use efficiency in relation to cropping system cultivar soil nitrogen and Rhizobial inoculation in semiarid environments. *Agric. Water Manage.* **97** 1375–1381. http://dx.doi.org/10.1016/j.agwat.2010.04.003

GRAEFF S, BINDER J, LINK J and CLAUPEIN W (2012) Crop models as decision support systems in crop production. INTECH Open Access Publisher. URL: http://www.intechopen.com/books/crop-production-technologies/crop-models-as-decision-support-systems-in-crop-production (Accessed 5 October 2015).

HARTKAMP AD, WHITE JW, RODRÍGUEZ AGUILAR M, BANZIGER M, SRINIVASAN G, GRANADOS G and CROSSA J (2001) Maize Production Environments Revisited: A GIS-based Approach. International Maize and Wheat Improvement Center (CIMMYT), Mexico.

JAT M and SATYANARAYANA T (2013) Fertiliser best management practices for maize systems. *Indian J. Fertil.* **9** 80–94.

KIRKHAM MB (2005) *Principles of Soil and Plant Water Relations*. Elsevier, New York.

KOUR R, SHARMA BC, KUMAR A and KOUR P (2013) Nutrient uptake by chickpea + mustard intercropping system as influenced by weed management. *Ind. J. Weed Sci.* **45** 183–188.

KUCHARIK CJ (2008) Contribution of planting date trends to increased maize yields in the central United States. *Agron. J.* **100** 328. http://dx.doi.org/10.2134/agrojnl2007.0145

LEHMANN N, FINGER R, KLEIN T, CALANCA P and WALTER A (2013) Adapting crop management practices to climate change: Modeling optimal solutions at the field scale. *Agric. Syst.* **117** 55–65. http://dx.doi.org/10.1016/j.agsy.2012.12.011

MABHAUDHI T, MODI AT and BELETSE YG (2013) Growth phenological and yield responses of a bambara groundnut (*Vigna subterranea* L Verdc) landrace to imposed water stress : II Rain shelter conditions. *Water SA* **39** 1–8. http://dx.doi.org/10.4314/wsa.v39i2.2

MODI AT, MABHAUDHI T, CHIMONYO VGP, HADEBE ST, and CHIBARABADA TP (2014) Determining water use of indigenous grain and legume food crops. Deliverable No.4 (unpublished), WRC Project No. K5/2274//4. Water Research Commission, Pretoria.

MBOW M, SMITH P, SKOLE D, DUGUMA L and BUSTAMANTE M (2014) Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Curr. Opin. Environ. Sustain.* **6** 8–14. http://dx.doi.org/10.1016/j.cosust.2013.09.002

MCCOWN RL, HAMMER GL, HARGREAVES JNG, HOLZWORTH DP and FREEBAIRN DM (1996) APSIM: A novel software system for model development, model testing, and simulation in agricultural research. *Agric. Syst.* **50** 255-271. http://dx.doi.org/10.1016/0308-521x(94)00055-v

MISRA AK (2014) Climate change and challenges of water and food security. *Int. J. Sustain. Built Environ.* **3** 153–165. http://dx.doi.org/10.1016/j.ijsbe.2014.04.006

MOLDEN D, OWEIS T, STEDUTO P, BINDRABAN P, HANJRA MA and KIJNE J (2010) Improving agricultural water productivity: Between optimism and caution. *Agric. Water Manage.* **97** 528–535. http://dx.doi.org/10.1016/j.agwat.2009.03.023

MOTSA NM, MODI AT and MABHAUDHI T (2015) Sweet potato response to low-input agriculture and varying environments of KwaZulu-Natal South Africa: implications for food security strategies. *Acta Agric. Scand. B Soil Plant Sci.* **65** 329–340. http://dx.doi.org/10.1080/09064710.2015.1011222

NOURI-GANBALANI A, NOURI-GANBALANI G and HASSANPANAH D (2009) Effects of drought stress condition on the yield and yield components of advanced wheat genotypes in Ardabil. *Iran. J. Food Agric. Environ.* **7** 228 – 234

OLEMBO KN, M'MBOYI F, KIPLAGAT S and OYUGI FK (2010) *Sorghum Breeding in Sub-Saharan Africa.* African Biotechnology, Nairobi.

OSENI TO (2010) Evaluation of sorghum-cowpea intercrop productivity in savanna agro-ecology using competition indices. *J. Agric. Sci.*

2 229–234. http://dx.doi.org/10.5539/jas.v2n3p229

OUDA SA, EL MESIRY T, ABDALLAH EF and GABALLAH MS (2007) Effect of water stress on the yield of soybean and maize grown under different intercropping patterns. *Aust. J. Basic Appl. Sci.* **1** 578–585.

ROSEGRANT MW, KOO J, CENACCHI N, RINGLER C, ROBERTSON R, FISHER M, COX C, GARRETT K, PEREZ ND and SABBAGH P (2014) *Food Security in a World of Natural Resource Scarcity Food security in a world of natural resource scarcity: The role of Agricultural Technologies.* International Food Policy Research Institute, Washington D.C.

SASRI (SOUTH AFRICAN SUGARCANE RESEARCH INSTITUTE (2015) SASRI Weather Web. URL: http://sasex.sasa.org.za/irricane/tables/Ash_tables_AR.pl (Accessed 5 October 2015).

SCHILLING J, FREIER KP, HERTIG E and SCHEFFRAN J (2012) Climate change vulnerability and adaptation in North Africa with focus on Morocco. *Agric. Ecosyst. Environ.* **156** 12–26. http://dx.doi.org/10.1016/j.agee.2012.04.021

THRUPP LANN (2013) Linking agricultural biodiversity and food security : the valuable role of agrobiodiversity for sustainable agriculture. *Int. Affairs* **76** 265–281.

UPCHURCH DR, MAHAN JR, WANJURA DF and BURKE JJ (2005) Concepts in Deficit Irrigation: Defining a Basis for Effective Management. *Proc. World Water Environ. Resources Congr* Paper No. 9028. May 2005. American Society of Civil Engineers, Reston VA.

VAN AVERBEKE W (2002) Indigenous Technology and technology-oriented research : implications for research methodology. *Proc. 18th Annual Conference AIAEE 2002*, 26–30 May 2002, Durban. 451–457.

VANLAUWE B, WENDT J, GILLER KE, CORBEELS M, GERARD B and NOLTE C (2014) A fourth principle is required to define Conservation Agriculture in sub-Saharan Africa: The appropriate use of fertilizer to enhance crop productivity. *Field Crop Res.* **155** 10–13. http://dx.doi.org/10.1016/j.fcr.2013.10.002

VENKATESWARLU B and SHANKER A (2009) Climate change and agriculture: adaptation and mitigation stategies. *Indian J. Agron.* **54** 226–230.

WANG J, LI X, LU L and FANG F (2013) Parameter sensitivity analysis of crop growth models based on the extended Fourier Amplitude Sensitivity Test method. *Environ. Model. Softw.* **48** 171–182. http://dx.doi.org/10.1016/j.envsoft.2013.06.007

WRC (WATER RESEARCH COMMISSION) (2014) WRC Knowledge Review 2013/14. Water Research Commission, Pretoria.

WYLIE P (2004) Managing sorghum for high yields. A blueprint for doubling sorghum production. Grains Development Research Council (GRDC), Kingston ACT.

APPENDIX 1

Rainfall

Rainfall varied across all sites and across months within each year (Table A1). In general, high mean rainfall was observed at Umbumbulu (900.1 mm) while low rainfall was observed in Deepdale with 647.63 mm per year (Table A1). On average, high (822.06 mm) but variable rainfall was observed at Ukulinga (19.60–98.71) while least variation was observed at Deepdale (11.18–37.82). The observed variations for Ukulinga rainfall would suggest that the risk of water related crop failures was high. On the other hand, rainfall received at Deepdale was stable but low, suggesting that if an ideal cropping system was adopted, the risk to crop failure would be low and stable yields could be observed.

TABLE A1
Comparison of mean rainfall and its variability across different environments (Richards Bay, Umbumbulu, Deepdale, Wartburg and Ukulinga)

Month	Richards Bay	Umbumbulu	Deepdale	Wartburg	Ukulinga
January	102.99 $^{\pm 93.48*}$	132.50 $^{\pm 54.22}$	98.35 $^{\pm 35.73}$	105.00 $^{\pm 35.89}$	133.46 $^{\pm 98.71}$
February	82.65 $^{\pm 55.51}$	76.32 $^{\pm 46.40}$	70.41 $^{\pm 31.86}$	77.43 $^{\pm 57.91}$	87.00 $^{\pm 55.19}$
March	83.77 $^{\pm 46.04}$	91.67 $^{\pm 44.11}$	72.08 $^{\pm 28.28}$	83.86 $^{\pm 34.98}$	111.36 $^{\pm 46.06}$
April	73.79 $^{\pm 48.28}$	62.35 $^{\pm 36.23}$	50.52 $^{\pm 31.25}$	73.85 $^{\pm 36.23}$	56.26 $^{\pm 48.28}$
May	24.87 $^{\pm 18.70}$	21.07 $^{\pm 19.28}$	17.03 $^{\pm 19.80}$	24.94 $^{\pm 18.82}$	23.16 $^{\pm 19.60}$
June	50.95 $^{\pm 70.01}$	22.49 $^{\pm 22.41}$	13.70 $^{\pm 11.18}$	46.76 $^{\pm 67.89}$	7.43 $^{\pm 61.76}$
July	26.87 $^{\pm 33.27}$	29.83 $^{\pm 61.76}$	14.49 $^{\pm 24.90}$	24.62 $^{\pm 33.77}$	13.46 $^{\pm 35.10}$
August	36.15 $^{\pm 59.34}$	35.38 $^{\pm 35.10}$	24.77 $^{\pm 25.03}$	33.17 $^{\pm 59.34}$	10.00 $^{\pm 50.54}$
September	57.64 $^{\pm 43.64}$	66.41 $^{\pm 50.54}$	37.65 $^{\pm 37.37}$	52.87 $^{\pm 43.64}$	35.63 $^{\pm 38.48}$
October	91.56 $^{\pm 41.37}$	108.67 $^{\pm 38.48}$	64.39 $^{\pm 22.07}$	83.96 $^{\pm 41.37}$	25.76 $^{\pm 45.91}$
November	98.00 $^{\pm 43.50}$	133.59 $^{\pm 43.55}$	84.70 $^{\pm 29.32}$	89.87 $^{\pm 42.87}$	95.27 $^{\pm 43.55}$
December	81.57 $^{\pm 33.70}$	119.85 $^{\pm 47.54}$	99.54 $^{\pm 37.82}$	74.83 $^{\pm 7.98}$	103.27 $^{\pm 67.87}$
Mean monthly	67.56	75.01	53.96	64.26	68.55
Mean yearly total	810.81	900.13	647.63	771.16	822.06

**Mean rainfall (mm) for 10-year (2004–2014) simulation. Superscript values correspond to the standard deviations.*