

## APPLYING APSIM FOR EVALUATING INTERCROPPING UNDER RAINFED CONDITIONS: A PRELIMINARY ASSESSMENT

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### ABSTRACT

Climate change and variability in rainfall pattern have amplified the effects of water scarcity in agriculture in semi-arid regions. Intercropping can improve crop productivity through increased water use efficiency (WUE). However, limited information exists to support its adoption and promotion. The Agricultural Production Systems Simulator (APSIM) model was used to develop best management practices for improved yield and WUE for a sorghum–cowpea intercrop system at Ukulinga Research Farm, Pietermaritzburg, South Africa. We considered planting dates, fertilizer application rates and irrigation. For both sorghum and cowpea, ideal planting date for high and stable yields [559.7 kg ha<sup>-1</sup> ( $\pm$  SD 258.42).and 220.7 kg ha<sup>-1</sup> ( $\pm$  SD 79.58), respectively] was 15 November. Adding fertilizer did not improve yield but increased WUE of the intercrop by 5.08%. Deficit irrigation was more effective at increasing yield (12.84%) but reduced WUE (-16.79%). APSIM can be used to develop best management practices for improving productivity of sorghum-cowpea intercrop systems under limited water conditions.

**Keywords** :Climate variability, Intercropping, Irrigation, Water Use Efficiency

### 1. INTRODUCTION

Within rural sub-Saharan Africa (SSA), achieving food security is continuously hampered by endemic poverty, high dependence on scarce water resources, and more importantly climate variability and change (Misra, 2014). Agriculture remains an important livelihood activity for achieving food security. However, crop productivity is low and insufficient to provide food and nutrition security for current and future demands (Rosegrant et al., 2014). Apart from socio-economic and bio-physical factors affecting productivity, climate variability and change has resulted in a shift and change in duration of growing seasons, increased incidences of seasonal dry spells and drought (Rosegrant et al., 2014). This has resulted in a reduction in agricultural water resources with formerly water scarce regions becoming water stressed (Schilling et al., 2012). Observed yields suggest that most rural farmers may not be equipped with necessary risk management skills to adapt to worsening water shortages (Venkateswarlu and Shanker, 2009). Therefore, to improve crop productivity, rural farmers should adopt cropping systems like intercropping that can adapt to drought. Secondly, there is a need to redesign current agronomic practices and also to develop decision support systems (DSS) that are geared towards mitigating risk to water stress.

Intercropping is the practice of growing two or more crops in proximity during the same time period (Willey, 1990). It is one of several sustainable intensification approaches, which have potential to improve productivity through efficient and complimentary use of resources such as land and water. The potential of intercropping, or any other farming system, can only be realised under proper agronomic management (Chimonyo et al., 2015). In addition, good agronomic practices can also improve adaptation strategies to risk of water stress (Zavattaro et

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al., 2015). However, due to observed changes in weather, current management options in intercrop systems may not always be the best to meet increased productivity under water stress. To increase productivity and further adoption of intercropping, there is need for a paradigm shift from current 'green revolution' agronomic practices to climate sensitive agricultural practices. This, in part, entails improving the capacity of farmers to make best management decisions. Crop simulation models (CSM) (McMaster et al., 2011) such as the Agricultural Production Systems Simulator (APSIM) (McCown et al., 1996) can be employed to generate quick and relevant information (Holzworth et al., 2014). We hypothesised that APSIM can aid in establishing best management strategies for intercrop systems. The objective of the study was, therefore, to apply a well-calibrated model of APSIM for a sorghum–cowpea intercrop in assessing different management scenarios for best management practices. This was achieved through scenario analyses based on long term (17 years) simulations. Planting dates, fertilizer rates and irrigation were factors considered for the scenario analyses.

## **2. METHODS**

### **2.1 Description of Environment**

Ukulinga Research Farm is classified as semi–arid with a mean annual rainfall of 790 mm, most of which is received between the months of October and April. The summer months are warm to hot with a temperature range of 18 - 38°C. Soils are derived from marine shales and the landform is colluvial fan and are classified as predominantly chromic luvisols. Soils are generally shallow and acidic with low to moderate fertility. Based on profile pit description, soil texture is clay to clay–loam with an effective rooting depth of 0.6 m. Results of soil chemical properties showed that the carbon (%) for the top 0.2 m layer was 2.3% while N was 0.3%. From these the initial C:N ratio was calculated as 7.67.

A three-step procedure was used for scenario analyses of sorghum –cowpea intercrop. These were (1) sensitivity analyses to identify model sensitive parameters, (2) parameterise and validate the model under local conditions, and (3) apply the model for different management scenarios.

### **2.2 Sensitivity Analyses**

Before the scenario analyses, sensitivity analyses was done to determine parameters which would have the most effect on model output. This involved adjusting one parameter at a time to values of  $\pm 10\%$  for default input parameters and then running the model. The percentage variation in simulated yields was compared with observed yield using relative sensitivity. Results of sensitivity analysis showed that the most sensitive parameters were management level parameters and these were planting dates, amount of fertilizer applied, soil pH and initial soil water content (results not shown). The importance of crop management has in risk management has long since been recognised by CSM developers. These parameters have been made sensitive so as to provide a broad response to large and variable agro-ecological zones. Based on the sensitivity analyses, scenario analyses was then formulated on the basis of planting dates, fertilizer application rates and irrigation.

### **2.3 Parameterisation and model testing**

Parameterisation and testing of the APSIM sorghum–cowpea model were done using data obtained from two year field experiments of a sorghum–cowpea intercrop established at the University of KwaZulu–Natal's Ukulinga Research Farm. For details of field experimental output and model performance, refer to Chimonyo et al. (2016)

## 2.4 Simulation

Simulations were performed using APSIM version 7.7. To simulate scenarios for the intercrop system within APSIM model, climate (MET file), crop (sorghum and cowpea), soil WAT and canopy modules were linked to the model engine. Modules also included were management, surface residue, irrigation and fertiliser. Details of model simulations are described below.

*Climate* - The MET file was developed using 17-year (1997 – 2014) weather data containing daily estimates of rainfall, minimum and maximum temperatures, solar radiation and reference evapotranspiration was obtained from an automatic weather station courtesy of the Agricultural Research Council – Institute for Soil, Climate and Water. The met files require average ambient temperature (TAV) and the annual amplitude in monthly temperature (AMP). These were calculated using long-term daily minimum and maximum temperatures. Calculated values of TAV and AMP were inserted in the model 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 requires 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. Available soil information was matched to pre-existing soils in the APSIM soil module. Soils at Ukulinga were described as shallow clayey to clayey loam with medium fertility (Mabhaudhi et al., 2013). The soil file selected in APSIM to best represent this description was Clay\_Shallow\_MF\_101mm (Table 1).

**Table 1:** Properties of the African (generic) soil series available in APSIM’s soil module with best describes soil water properties in Ukulinga (the effective root zone for crops was considered to be 0-60 cm)

Depth (cm)	Bulk density (g cm <sup>-3</sup> )	Air Dry <sup>1</sup>	LL15 <sup>2</sup>	DUL <sup>3</sup>	SAT <sup>4</sup>
		(mm mm <sup>-1</sup> )			
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

<sup>1</sup>Air Dry – Hygroscopic soil water content; <sup>2</sup>Crop lower limit (LL15) – Permanent wilting point (PWP) lower limit of the available soil water range and is a point when plants have removed all of the available water from a given soil, they wilt and will not recover <sup>3</sup>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 approximately 24 hours <sup>4</sup>Saturation (SAT) - Saturation is when all pores in a soil are filled with water.

## 2.5 Scenarios analyses

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

### *Scenario 1: Planting dates*

Based on the methodology outlined by Chimonyo et al(2016), three approaches were used to establish planting dates and these were, trigger season climate method, modelling and fixed date approach. Briefly, the trigger season method is used to determine the onset or planting date and length of a growing season from long term weather data (White et al., 2001). 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. 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  $0.5 ET_o$ . For this study, planting dates, as defined by the onset of the growing season, were established based on 17 year monthly averages of rainfall,  $ET_o$  and  $0.5 ET_o$  was the 17<sup>th</sup> of October.

The fixed planting date method used a range of five planting dates covering a period from 15 September to 15 January. Planting dates used were 15<sup>th</sup> of September, October, November, December and January, and these dates represented early to late planting.

Most crop simulation models are able to generate planting dates from climate and soil data. Based on a predefined criteria, the model takes into account amount of rainfall and days taken to achieve desired quantity. In addition, soil water content within the seedling zone is considered. Planting dates were generated using APSIM from a user defined criteria of 'sum of rainfall in a 10 day period where at least a cumulative amount of 20 mm is received' (Raes et al., 2004). In addition, a fixed soil water content of 80% of field capacity of the top 15 cm was considered. The criteria set reflected planting conditions often used by farmers in semi-arid regions where planting is often done after the onset of the rainy season. Across the years, frequencies of planting dates falling in similar months were observed and mean planting date for that month was calculated. For evaluating yield and WUE, planting date with the highest frequency of appearance within the 17 year weather data set was used for scenario analysis. Based on the analysis it was observed that 20<sup>th</sup> of November had the highest frequency (12 out of 17 years).

#### *Scenario 2: Fertilizer application rates and time of application*

Based on soil analysis, sorghum fertilizer required  $72 \text{ kg N ha}^{-1}$  to achieve tonnage of between  $1 - 1.5 \text{ t ha}^{-1}$  at Ukulinga farm. Grain sorghum yields in SSA average  $\approx 900 \text{ kg ha}^{-1}$  as compared to the world average of  $1.5 \text{ t ha}^{-1}$  (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 et al., 2007). 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 all (100%) recommended N requirements.

#### *Scenario 3: Irrigation*

Water stress is the main cause for observed yield gaps occurring in rainfed farming systems, therefore, we considered supplementary irrigation as a management option. Deficit irrigation and rainfall based approaches were considered for irrigation scheduling. Deficit irrigation (ASWD) involves irrigating below full crop water requirement in such that there is little yield reduction and water is saved (Upchurch et al., 2005). For this scenario, allowable soil water depletion of 40% of plant available water (PAW) was defined before irrigation refilled it back to 80% of PAW. This ensured that soil water content never reached levels that could cause water or aeration stress to the plant. In semi-arid conditions, rainfall is often unevenly distributed resulting in intermittent water stress and hence causing considerable yield losses (Nouri-ganbalani et al., 2009). Therefore, weekly rainfall was used to schedule irrigation. The condition was 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.

### 3. Data Analyses and Evaluation

Using model outputs, WU was determined as the sum total of crop water uptake from the whole profile (sorghum Ep + cowpea Ep), soil evaporation (Es), runoff and drainage. Since APSIM does not calculate WUE directly, simulated outputs (WU, yield and biomass) were used to determine WUE as follows:

$$WUEy = \frac{Y}{WU} (kgmm^{-1}ha^{-1}) \quad \text{Equation 1}$$

where: WUE = water use efficiency ( $kg\ mm^{-1}\ ha^{-1}$ ), Y = total grain yield (sorghum + cowpea) ( $kg\ ha^{-1}$ ), ( $kg\ ha^{-1}$ ) and WU = the crop water use (WU) (mm). Descriptive statistics such as means, standard deviations, and box and whisker plots were used to analyse outputs. Box and whisker plots can show stability and general distribution of the sets of data.

## 4. RESULTS AND DISCUSSION

### 4.1 Rainfall

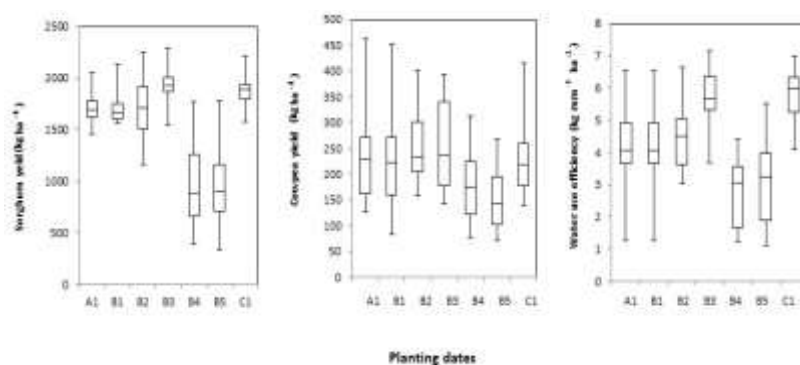
Within the growing period (October – April) rainfall fluctuated across simulation years. High amounts of rainfall were observed in 1999 with 603.8 mm while low rainfall was recorded in 2000 (262.00 mm), 2009 (289.30 mm) and 2013 (259.7 mm) (Fig. 1). There was high inter-seasonal variation as shown by a large standard deviation of  $\pm 96.26$  mm. Overall, the trend for rainfall showed a gradual decrease (slope = -3.44) from 1997 to 2015. This was attributed to more years (6 out of 9) in the latter half of the simulation period receiving less than the average mean rainfall of 374.11 mm (Fig. 1). These findings are consistent with observations by several authors who project a gradual decrease in rainfall by 2050 within southern Africa ( Engelbrecht et al., 2009; Crétat et al., 2012; Dai, 2013; Fraser et al., 2013). These results reaffirm the need to come up with farming systems that are adaptable to low water availability.



**Figure 1.** Rainfall received during the growing period (October – April) over 1997 – 2015.

## 4.2 Planting Dates

Different planting dates gave different mean yields and mean yield distribution for sorghum and cowpea. Based on the observed results, simulated average yields for sorghum and cowpea were  $1559.7 \text{ kg ha}^{-1}$  ( $\pm \text{SD } 258.42$ ) and  $220.7 \text{ kg ha}^{-1}$  ( $\pm \text{SD } 79.58$ ), respectively (Fig 2). An ideal planting date is a scenario where overall yields are high and there is less variation over time (Kucharik, 2008). For Ukulinga, 15-November was ideal as it gave high and stable yields for sorghum and cowpea [ $1895.20 \text{ kg ha}^{-1}$  ( $\pm \text{SD } 176.08$ ) and  $177.80 \text{ kg ha}^{-1}$  ( $\pm \text{SD } 65.76$ ), respectively] (Fig 2). The observed results were attributed to higher soil water content and increased frequency in rainfall during that time period, relative to earlier or later planting dates. Furthermore, it was observed that flowering occurred after the observed mid-season break which occurred in the first and second week of January. Conversely, WUE was significantly higher and more stable when the intercrop system was planted on 15-November. Improvements in WUE were associated with low water use by the system coupled with increased yields (Fig 2). The low water use observed was due to less water lost through unproductive means (soil evaporation, runoff and drainage) relative to the other planting dates. Results, therefore, suggest that 15-November planting date could be ideal for farmers within semi-arid-arid region, similar to Ukulinga, plant sorghum–cowpea intercrop system.



**Figure 2.** Simulated yield response of sorghum-cowpea intercrop system for different planting date scenarios (A- site specific planting date defined by trigger season method; B – fixed planting dates starting from 1 – 15 Sept, 2 – 15 Oct, 3 – 15 Nov, 4 – 15 Dec, 5 – Jan; C – planting dates generated by APSIM).

## 4.3 Fertilizer Application

Over the simulation period results showed that improving soil N improved yields slightly (5.21%) (Table 2). This would suggest N was not a limiting factor at the site. Overall, adding N fertiliser had a positive (5.08%) (Table 2) effect on WUE and this improvement could have been attributed to the observed increase in yield for sorghum in response to fertilizer application. Improving N fertility in poor soils improves water use by enhancing photosynthetic capacity of leaf through improved enzyme function which results in increased carbon dioxide assimilation (Deng et al., 2006). Observed interaction between WUE and N fertilizer are in line with results by Li et al. (2015) who observed an improvement of WUE with additions of different rates of N fertilizer. Under rainfed cropping systems, application of fertilizer should always be considered as it has been observed to improve yield, WUE and resilience to climate change.

**Table 2.** Yield simulations of sorghum-cowpea intercrop system, water fluxes and water use efficiency of the system in response to fertilizer

Fertilizer amount (kg N ha <sup>-1</sup> )	Yield (kg ha <sup>-1</sup> ) <sup>1</sup>		Water fluxes (mm)		Water use efficiency (kg mm <sup>-1</sup> ha <sup>-1</sup> )
	Sorghum	Cowpea	Water lost <sup>2</sup>	Transpiration	
0	1825.82	246.93	279.65	90.98	5.68
36	1924.73	246.70	280.10	94.59	5.89
72	1919.26	246.61	280.52	94.98	5.91

<sup>1</sup>Yield average over 17 year period; <sup>2</sup>Water lost through unproductive ways such as runoff, drainage and soil evaporation

#### 4.4 Irrigation Scheduling

Irrigation marginally improved (5.62%) productivity of the sorghum–cowpea system but had a negative effect on WUE (Table 3). The improvement in overall yield was attributed to the large and positive (26.35%) effect of irrigation on yield for cowpea. This could be because more water was made available for cowpea which is considered as the less dominant crop since it has a shallower rooting system. Scheduling irrigation based on weekly rainfall events (WIR) resulted in wasteful water use as indicated by large amounts of water lost through unproductive means. It could be that there was over application of water relative to crop water requirements (Jumman, 2008). Yields of both sorghum and cowpea were more stable under ASWD (standard deviation ±163.53 and 75.35, respectively) in comparison to RF (standard deviation ±190.38 and 95), and WIR (standard deviation ±195 and 95) over the 17 year simulation period (Table 3). This could be because ASWD ensured that soil water was always available and did not fluctuate greatly.

Overall irrigation reduced WUE of the intercrop system relative to WUE observed under rainfed conditions. This could be attributed to high amounts of water lost through unproductive means under irrigation relative to rainfed conditions. This confirms early observations were, although yield improved, high amounts of water were lost through unproductive use. Conversely, results of WUE show that irrigating based on ASWD resulted in high (31.47 %) WUE of the intercrop system relative to WIR (Table 3). Similarly, the observed results could be attributed to large amount of applied water being lost through unproductive use. In this regard, ASWD can be suitable to improve yield of the intercrop system; however, to further increase WUE, more irrigation water management options are required.

**Table 3:** Yield simulations of sorghum-cowpea intercrop system, water fluxes and water use efficiency of the system in response to irrigation

Water regime	Yield		Water fluxes				WU	WUE	
	Sorghum	Cowpea	Water lost	Transpiration		Irrigation			Rainfall
RF	1916.3	246.6	286.4	33.9	60.1	0	404.6	380.4	5.68
WIR	1941.8	312.1	520.0	45.9	61.8	201.1	404.6	627.8	3.59
ASWD	1938.0	309.8	378.4	45.3	64.6	67.6	405.6	488.4	4.72

<sup>1</sup>Yield average over 17 year period; <sup>2</sup>Water lost through unproductive ways such as runoff, drainage and soil evaporation

## 5. CONCLUSIONS

The model APSIM was efficient at assessing yield responses for sorghum–cowpea under different management scenarios. In addition, the model was able to identify best management practices for improved water use efficiency for sorghum–cowpea intercrop under rainfed conditions. Different management options resulted in different yield response for sorghum–cowpea intercrop systems. Sorghum–cowpea intercrop system was most responsive to changes in planting dates while moderate changes were observed in response to fertilization and irrigation. The model APSIM can be used to develop best management practices for improving productivity of sorghum–cowpea intercrop systems under limited water condition.

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