Article

Evaluation of FAO AquaCrop Model for Simulating Rainfed Maize Growth and Yields in Uganda

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Abstract: Uganda's agriculture depends mainly on rainwater. As farmers are trying to increase on the food output to match the demands of a fast growing population, they are susceptible to make losses due to fluctuating weather patterns which are being caused by the global climate change. Therefore, it is necessary to explore ways of improving water use efficiency in rainfed agricultural systems to save farmers labour and input costs in situations where the grain harvest would be zero due to crop failure. The water driven FAO AquaCrop model is used as a support tool for making informed decisions during planning and situation analysis. In this study, AquaCrop model was evaluated for prediction of maize growth and yields at MUARIK in Uganda, for rainfed agriculture in three growing seasons. The model efficiency (E) and root mean square value (RMSE) for the maize canopy simulation during the September-December 2015 season was 0.945 and 7.24 respectively. The deviation of the simulated final biomass from measured data ranged from -15.4 to 11.6%, while the deviation of the final yield ranged from -2.8 to 2.0. The results suggest that the model can be used in the prediction of rainfed agricultural outputs, hence helping in guiding on management practices to increase food production.

Keywords: AquaCrop model, Maize, Rain fed, Uganda

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1. Introduction

Maize is an important cereal crop cultivated on over 23.4% of the land for food crops in Uganda (Ubos, 2016). Currently maize is a major staple for the low earners in rural and urban areas, giving a variety to house hold and institutions (schools, prison, factories and many others) diets in form of roasted green cobs, steamed green cobs and maize flour prepared as posho or porridge. Maize is a source of income for the smallholder famers providing a living to over 3.8 million Ugandans and a source of government revenue through foreign exchange, contributing over US$ 100 million in forex earnings (Ubos, 2016).

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Uganda's agriculture mostly depends on rainfall which is distributed in a bimodal pattern, with short rains coming between March to June and the long rains from September to December, annually amounts ranging between 800 to 1300 mm. This enables two seasons in central and southern Uganda (September to December and March to June) and one season in northern Uganda (October to January) in a year with just sufficient rainfall averagely ranging between 800 to 1500mm annually.

However, the dependence on the nature for agricultural production has become unreliable being compromised by climate change especially rainfall season fluctuation (Rockström and Barron, 2007; USAID, 2013) which has affected food production. FAO data indicates that crop output is only 2.763 million tons and the yield is fluctuating at 2.5 tons per hectare (FAO, 2017). This output can't match up high population growing at a rate of 3.2% (UBOS, 2013) hence threatening the food security. In 2013, WFP reports that Uganda is food insecure with 6% of Ugandans surviving on one meal a day, 14% of children stunted and 48% of Ugandans are food energy deficient (WFP, 2013).

Alternative efficient and effective food production systems are required to feed these high populations. However, these systems require more water use yet agricultural water use faces competition from other sectors like municipal, industrial, and ecological (Republic of Uganda, 2010). Although smart irrigation water saving technologies have been developed, Ugandan agriculture is dominated by small and medium scale farmers with a national average land holding size of 1.1 ha (UBOS, 2010) who cannot afford the investment and maintenance cost of such systems, and thus practices rainfed agriculture. Thus, there is need to accurately predicate yields (biomass and grain harvest) of staples like maize (Zea mays) to save farmers labour and input costs in situations where the grain harvest would be zero due to crop failure. Rockström et al. (2007) showed that it is possible to at least double rainfed staple food production by producing more 'crop per drop' of rainwater. Crop yield simulation models like APSIM (Wang et al., 2002), DSSAT (Jones et al., 2003), FAO AquaCrop (Raes et al., 2012) has been widely used as decision support tools in the agricultural sector.

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However, these models are often applicable only to the fields for which they are calibrated and require a number of parameters for their application, hence making them hard to be applied in developing countries like Uganda where there is a challenge of data collection due to inadequate equipment and funds to conduct research.

In 2009, FAO developed the AquaCrop model originating from the ‘‘yield response to water’’ (Doorenbos and Kassam, 1979) to a normalized crop water productivity concept (Raes et al., 2009a; Steduto et al., 2009). Compared with other models, AquaCrop is relatively simple to operate by people with little or no research experience and this robust model requires a limited set of input parameters, most of which are relatively easy to acquire (Steduto et al., 2009, Hsiao et al., 2009). The AquaCrop model is also capable of simulating crop performance in multiple scenarios

This model has been tested for various crops in different environments for example maize in California, USA (Hsiao et al., 2009), maize in Zaragoza, Spain (Heng et al., 2009), barley in Ethiopia (Araya and Kebede. 2009), maize in Kenya (Ngetch et al., 2012) and many others. Therefore the purpose of this study was to assess the capability of AquaCrop model to simulate the growth and yields of maize in Uganda.

2. Materials and Methods

Description of the Study area

The study was conducted at Makerere University Agricultural Research Institute Kabanyolo (MUARIK), Wakiso district, Uganda (Latitude 0º 28’00.38” N, Longitude 32º 36’46.01” E and 1161 m above sea level).

MUARIK is characterized by a typical tropical climate with maximum temperatures of 28.5ºC and minimum temperatures of 14ºC. The mean annual rainfall approximates to 1200mm in a bimodal distribution with the short rains coming between March to June and the long rains from September to December. The soil type of the area is clay-loamy.

Longe5, a local cultivar commonly grown by farmers was used in the experiment and the local practices of farm management (ploughing, weeding, pest management, no fertilizer

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amendments) were followed. Some of the relevant information required for model running is presented in the Table 1.

Table 1. Experimental and agronomic data

Parameter	Sept-Dec, 2014	Mar-Jul, 2015	Sept-Dec, 2015
Plant population, plants ha^{-1}	66,667	50,000	53,333
Sowing date	12/09/2014	25/03/2015	14/09/2015
Number of days from sowing to emergence	7	6	6
Number of days from sowing to flowing	73	72	66
Number of days from sowing to maturity	104	107	107
Seasonal rainfall, mm	542	302	589.8
Seasonal reference evaporation, mm	555	519	690.6

Model input data

Weather data (Rainfall, net horizontal solar radiation, wind speed, temperature and relative humidity), were obtained from the farm's weather station while the Mean annual atmospheric carbon dioxide concentration measured at Mauna Loa Observatory in Hawaii are provided in AquaCrop for past years (Heng et al., 2009). The daily reference evapotranspiration (ETo) for each growing season was calculated based on the FAO Penman-Monteith method (Allen et al., 1998) using the ETo calculator (FAO, 2009).

Soil samples were collected from the study area in their respective horizons for laboratory analysis. Soil properties laboratory analysis results are presented in Table 2. However, permanent wilting point moisture content (Θ_{wp}), field capacity moisture content (Θ_{fc}) and hydraulic conductivity at saturation (k_{sat}) were the only properties as the model inputs as recommended by Heng et al (2009).

Table 2. Soil properties of the study area.

Depth (cm)	%sand	%Clay	%Silt	pH	BD (g/cm^3)	θ_{pwp} (%)	θ_{fc} (%)	θ_{sat} (%)	K_{sat} (cm/hr)
0-15	33	37	30	5.3	1.33	19	31	51	0.250
15-30	29	45	26	5.4	1.35	20	32	51	0.248

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30-45	26	50	24	5.5	1.35	17	28	45	0.205
45-60	25	56	19	5.3	1.36	16	26	40	0.121

AquaCrop model uses three categories of crop parameters; conservative parameters (Table 3) which do not necessarily change with time, location, cultivar or management practices (Heng et al., 2009; Hsiao et al., 2009) and they are provided with in the model. Management and cultivar specific parameters are also required by the model, these vary with cultivar and management. Some of these parameters are presented in Table 1.

Table 3. Conservative parameters used in the simulations.

Parameter and unit	**Value**
Base temperature, °C	8.0
Upper temperature, °C	30.0
Soil surface covered by an individual seedling at 90% emergence, (cm^2/plant)	6.5
Canopy growth coefficient (CGC), % increase/day	13
Canopy decline coefficient (CDC), % decrease/day	10
Crop determinacy linked with flowering	Yes
Excess of potential fruits, %	50
Shape factor describing root zone expansion	1.3
Crop coefficient when canopy is complete but prior to senescence	0.95
Decline in crop coefficient after reaching maximum CC, % decline day^{-1}	0.30
Water productivity normalized for ET_0 and CO_2, WP* (g/m^{-2})	33.7
Water productivity normalized for ET_0 and CO_2during yield formation (as % WP* before yield formation)	50
Coefficient describing negative impact of stomatal closure during yield formation on HI	3.0
Possible increase (%) of HI due to water stress before flowering	None
Coefficient describing positive impact of restricted vegetative growth during yield formation on HI	Small
Coefficient describing negative impact of stomatal closure during yield formation on HI	Strong
Maximum possible increase in specified HI, %	15

Description of AquaCrop Model

The model was proposed by FAO in 2009 with the details outlined in Steduto et al., 2009, and Raes et al., 2011. The model relates its components (the soil, the crop and the atmosphere) through soil and water balance, the atmosphere (precipitation, temperature, evapotranspiration and carbon dioxide concentration) and crop conditions (phenology, crop cover, root depth, biomass production and harvestable yield) and field management

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(irrigation, fertility and field agronomic practices) components (Raes et al., 2009a; Steduto et al., 2009). It computes the daily water balance and separates the evapotranspiration into evaporation and transpiration. Transpiration is associated to canopy cover which is proportional to the scope of soil cover whereas evaporation is related to the area of soil not covered. As the crop mature, it responds to water changes through four stress coefficients (leaf expansion, stomata closure, canopy senescence, and change in harvest index). AquaCrop uses a normalized crop water productivity (WP*) for calculating the daily aboveground biomass production (Hsiao et al., 2009; Steduto et al., 2009), which is considered constant for a given climate and crop. The yield is obtained by multiplying biomass with the harvest index (HI). HI for maize is set between 48 and 52 percent.

Field Data Collection

Canopy cover values during growing season were obtained through taking aerial images of randomly selected representative plants from the experimental plot. The images were analyzed in the imagej software (Tiago and Rasband, 2012) to obtain the canopy cover.

Final biomass and grain yield was obtained following maturity using samples obtained from the experimental plot. The final above ground biomass samples were collected by cutting the crop at the ground level, oven dried for two days and weighed on the a digital weighing scale. The final yield samples were also harvested, dried to 12.5% moisture content in the drier and weighed on the digital scale.

Model evaluation criterion

The model was calibrated using measured canopy cover accumulation values for the Sept – Dec, 2014 growing season. The model was run after entering all the input data sets and an iterative process was conducted, by adjusting the model parameters till the best match between the simulated and measured data from the field was obtained. The validation was done using the measured final biomass and grain yield against simulated values for all the tree seasons.

The performance of the model was evaluated using statistical parameters which include; Root mean square error (RMSE) and Model efficiency (E). E accesses the predictive power of the model (Nash and Sutcliffe, 1970). while RMSE indicate the error in model prediction; these statistical indices were used to compare measured and simulated values.

$$E = 1 - \frac{\sum_{i=1}^{N}(O_i - S_i)^2}{\sum_{i=1}^{N}(O_i - \overline{O})^2} \qquad (3.1)$$

Where S_i and O_i are the simulated and observed data, $\overline{O}_i$ mean value of O_i and N is the number of observations.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i - S_i)^2}{N}} \qquad (3.2)$$

RMSE measures the overall deviation between observed and simulated values, estimating the model uncertainty. It takes the same units of the variable being simulated, and therefore the closer the value is to zero, the better the model simulation performance. However, E has compared to RMSE evaluates the model performance over entire simulation period. RMSE does not account for the large deviations occurring in some part of the season and small deviations in other part of the season, E accounts for the different deviations, as they depart from ($O_i - \overline{O}$) along the season and expresses an efficiency of the model performance, that is, the smaller the departure from ($O_i - \overline{O}$), the higher the performing efficiency of the model. E is unit less and may assume values ranging from –∞ to +1, with better model simulation efficiency when values are closer to +1.

3. Results and discussion

Canopy cover

The simulated and observed canopy cover values during the Sept–Dec, 2014 growing season are shown in Figure 1. Aqua Crop could simulate the canopy cover development for the entire growing season

The E and RMSE values for canopy cover simulation are 0.945 and 7.24 respectively. According to Heng et al. (2009) on validating the FAO AquaCrop model for irrigated and

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water deficient field maize, in Gainesville, the RMSE in canopy cover simulations was 34.53 % for rainfed, and according to Hsiao et al. (2009) on maize growth simulation with AquaCrop model, the RMSE in canopy cover simulations was 7.58 %. Therefore, the AquaCrop model has a good simulation for maize canopy cover a representation of maize growth.

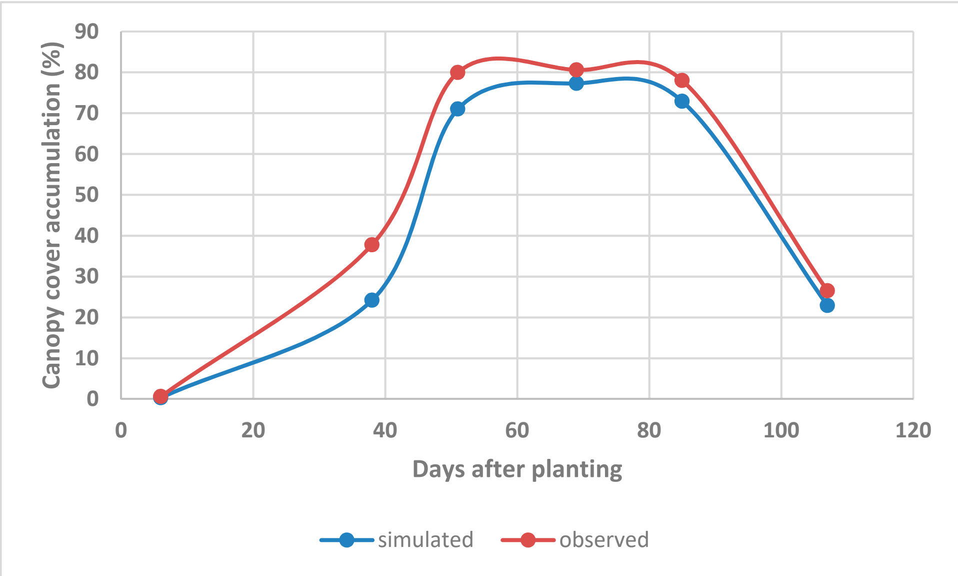

Figure 1. Canopy cover development for the September - December, 2014 growing season.

Final biomass and grain yield

Figure 2 and 3 shows the comparison of the simulated and observed yield and biomass for all the growing seasons. Also, the values of simulated and observed yield and biomass and percentage deviations are presented in Table 4. The results showed that the model has simulated grain yield better than the biomass. The values of RMSE and E for final yield and biomass simulations are also presented in Table 5.

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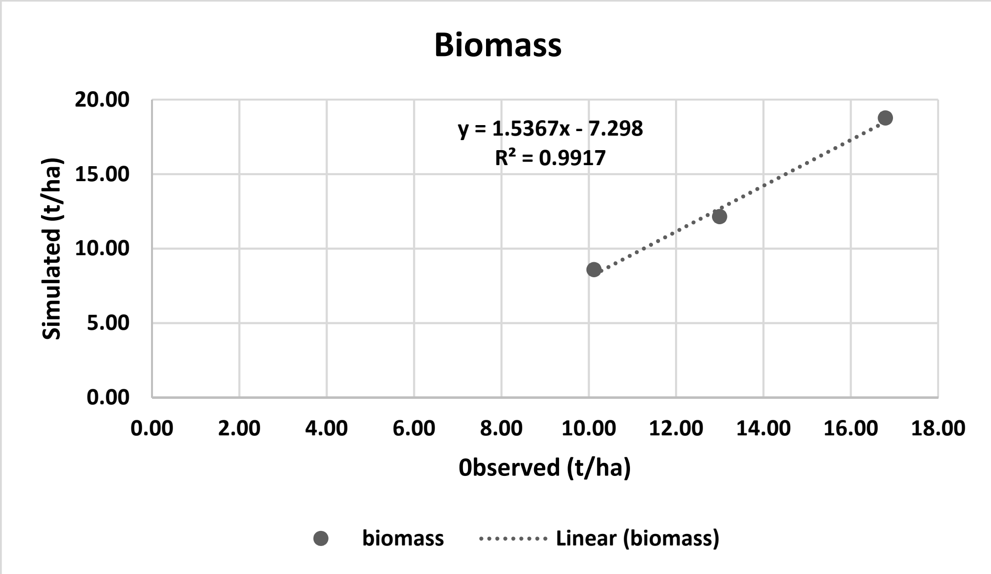

Figure 2. Simulated vs. measured final above ground biomass for all the three growing seasons.

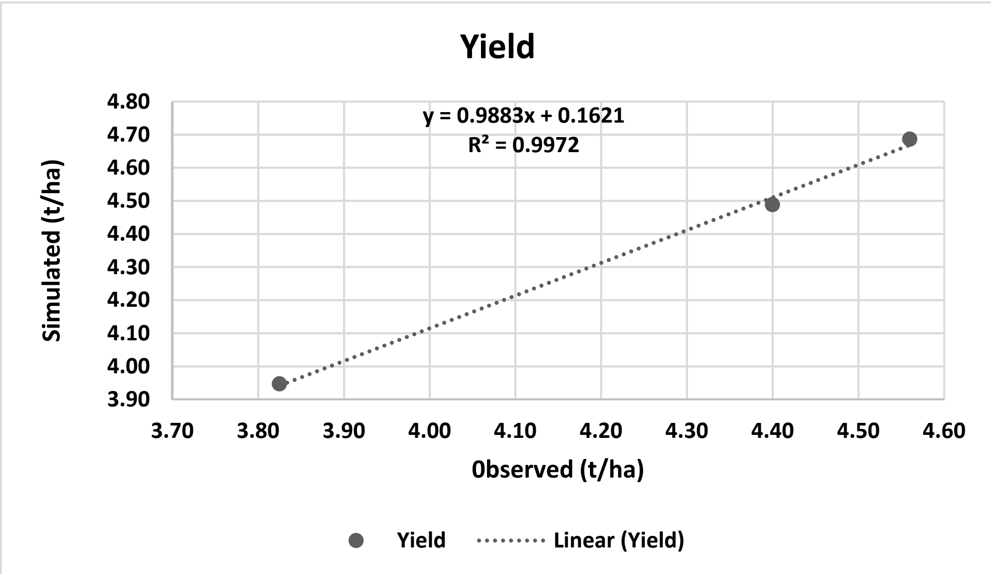

Figure 3. Simulated vs. measured final grain yield for all the three growing seasons.

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The values of simulated and observed yield and biomass and relative error percentage of those simulations are presented in Table 4. The relative errors of simulated biomass and yield ranged between -6.6% to 11.6% and 2.0% to 3.2%, respectively. The results showed that the model simulated grain yield better than the biomass.

From the results, it is observed that, the model under simulated the final biomass as compared to the final yield, hence the negative percentage deviations for final biomass and

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positive deviations for final yield except for the third season. However, these results, both final yield and biomass are comparable to the maize simulation results (Hsiao et al., 2009; Mebane et al., 2013) and sweet sorghum simulation results (Stricevic et al., 2011).

Maize production of the Sep - Dec, 2015 growing season was greater compared to the proceeding seasons, as reflected in both final biomass and yield results. This was attributed to the low seasonal rains with high seasonal evapotranspiration (Table 1), consequently affecting crop production.

Table 4. Measured vs simulated values of the final above ground biomass and grain yield.

Growing season	Biomass (t/ha)			Grain yield (t/ha)		
	Measured	Simulated	Deviation (%)	Measured	Simulated	Deviation (%)
Sept–Dec,2014	13.00	12.14	- 6.6	4.40	4.49	2.0
Mar–Jul, 2015	10.13	8.57	- 15.4	3.83	3.95	3.2
Sept–Dec,2015	16.80	18.75	11.6	4.56	4.69	-2.8

Statistical evaluation of the AquaCrop performance for the all the growing seasons show a better simulation for the yield than the biomass (Table 5). Araya et al. (2010) study on simulating biomass and yield of barley, the E values for biomass and yield simulations were obtained between 0.53 to 1 and 0.5 to 0.95 and the RMSE values were obtained between 0.36 to 0.9 t ha^{-1} and 0.07 to 0.27 t ha^{-1}, respectively. In Hsiao et al. (2009) to simulate biomass and yield of corn using AquaCrop model, the RMSE values for biomass and yield simulations were obtained between 0.46 to 6.51 t ha^{-1} and 0.65 to 1.33 t ha^{-1}, respectively. Basing on the results of this study, AquaCrop model can simulate the growth of maize.

Table 5. Statistical values for evaluating the performance of the AquaCrop model in simulations of final above ground biomass and grain yield for all the three seasons.

	Biomass	Grain yield
RMSE (t/ha)	1.52	0.11
E	68.9	87.1

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4. Conclusions

The FAO AquaCrop model was able to simulate well the growth and yield of maize. Therefore, the model can be used as a decision support by agricultural district production managers, consultants and irrigation engineers in helping rainfed practicing farmers make informed decisions. In this experiment, the model best simulated the final grain yield compared to the final above ground biomass yield. However, Statistical figures show that the research carried out for only three growing seasons with no treatments was not adequate enough to fine-tune the model so that it can be put in practice. For that case, the model should be tested with supplementary setups of research, if possible including irrigation and cumulative biomass and yields such that the comparison can be viable enough to verify the validity of the model for application in Uganda.

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