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Evaluation of CROPWAT 8.0 model in predicting the yield of East Africa Highland banana under different sets of irrigation scheduling

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ABSTRACT

Simulation models based on plant physiology are used to predict growth and yield of crops. Such models are important because they can be used to pre-evaluate treatments, thus, improving the effectivity of agricultural research and reducing the cost of field experiments. For efficiency purpose, crop models need to be calibrated and validated before using them. The objective of this study was to evaluate the performance of an existing crop model in predicting the yield of East Africa Highland banana (EAHB) under deficit irrigation and different irrigation intervals. The model, CROPWAT 8.0, was calibrated, evaluated and applied for banana crop water requirements and estimation of EAHB yield. For calibration of CROPWAT 8.0, monthly climatic data (temperature, relative humidity, wind speed, sunshine hours and rainfall), crop and soil data are were used. Climatic data were provided by the New_LocClim software which is the local climate estimator of FAO, effective rain was set to zero because the experiment was conducted under a rain shelter. Three irrigation levels (IL) (80%, 90% and 100% of Evapotranspiration) were combined with three levels of irrigation intervals (D) (4, 6 and 8 days in a randomized complete block design (RCBD) with three replications. To evaluate the model for yield estimation, the observed yield was compared with the corresponding simulated values by CROPWAT 8.0 using mean squared deviation (MSD), Nash and Sutcliffe model efficiency (NSE), coefficient of determination (R^2) and paired t-test. The predicted banana yield (39.1 ± 2.66 t ha^{-1}) from the calibrated model was very close to the observed yield (38.4 ± 2.37 t ha^{-1} ($p \geq 0.05$, R^2 = 0.82 and an NSE of 0.81. MSD analysis showed that the model's prediction was more accurate at 8 or 6 days irrigation intervals than 4 days irrigation interval. The calibrated CROPWAT 8.0 model can be used efficiently to predict the yield of East Africa Highland banana.

Keywords: CROPWAT 8.0, banana yield, deficit irrigation, irrigation interval

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1 Introduction

Agricultural water management approaches through irrigation scheduling are of vital interest for crop yield improvement and increasing economic return. Irrigation scheduling brings solutions on when and how much to irrigate a crop for efficient use of water; here, crop models can play a vital roles (Li et al., 2014; Batte et al., 2019; Oteng-Darko et al., 2013; Asseng et al., 2013). Crop models mimic the behaviour of crops by foreseeing their growth and yield (Oteng-Darko et al., 2013; Thornley and Johnson, 2000). Those are also useful for assessing the impacts of climate change in agriculture and are applied to inform planning and policies at various levels (Steduto et al., 2009).

With respect to irrigation scheduling, simulation models are used by scientists, farmers, agricultural extensionists and decision-makers to estimate the amount of water to irrigate and when to apply water to crops. The models are also used to generate and assess performance of deficit irrigation schedules for different crops. Irrigation scheduling models are important tools in water management since they are capable of simulating alternative irrigation schedules with different levels of acceptable soil water depletion (Fortes et al., 2005; Pereira et al., 2003). Those models are evaluated from the relative yield loss occurred when full crop water requirement demand is not met (Fortes et al., 2005).

Several crop simulation models have been developed for major cereal crops like rice, maize, wheat (Li et al., 2014; Batte et al., 2019; Asseng et al., 2013) and potato (Fleisher et al., 2016). Banana is an important crop in the world, but only few models have been developed and studied for this crop including Global Environmental Stratification (GEnS), Species Distribution Modelling (SDM), Ecological Niche Modelling (ENM) SIMBA cc, LINTUL BANANA 1 (Zhao et al., 2019; Ranjitkar et al., 2016; Tixier et al., 2011; Nyombi, 2010). Although crop models are very useful, they have limitations. Some of the biological, physiological and processes in agriculture are not fully understood due to computer-based limits in matching the complex natural growth systems of plants. In some cases, variations between models' outputs and natural systems cannot be fully explained, therefore, crop models need to be validated (Oteng-Darko et al., 2013) towards achieving the closest fit between the natural and the modelled characters.

One of the crop models that has been used on banana is CROPWAT 8.0 model; the model is a computer software capable of estimating crop yields, crop water and irrigation requirements based on data of the climate, rain, soil and crop. CROPWAT 8.0 can also be used to assess farmers' irrigation practices and estimate crop performance under rainfed and irrigated conditions (FAO, 2009). The model calculates the reference crop evapotranspiration (ET_o) using the Penman-Monteith method which is currently the recommended method by FAO (Naik et al., 2015). The model was used in this study for it requires minimal input data and does not require important calibration for local conditions. Input data for weather were provided by 'New_LocClim' which is a computer program to approximate local climatic conditions for any position on earth. It employs the FAO agroclimatic information with data from approximately 30,000 stations (Grieser et al., 2006; FAO, 2005). New_LocClim is essentially an improved version of LocClim (Local Climate Estimator) also developed by FAO (2002).

Currently, there has been a growing scarcity of water resources and competition for water among users in many countries of Africa and worldwide (Gashu et al., 2019). Due to growing populations, there is an increase in water demands to meet food and human needs. One of the solutions to overcome this challenge is to use existing water resources more efficiently (George et al., 2000). One of the techniques used to improve irrigation water use efficiency is deficit irrigation. This technique refers to the application of water below the optimum amount of water required by the crop (evapotranspiration) without affecting significantly the crop yield. With deficit irrigation, water is applied at constrained levels during a particular period or during the whole growing season (Enchalew et al., 2016; Fereres and Soriano, 2006).

Banana is a very important fruit in the world and affordable staple food in East Africa. It is a perennial crop grown by smallholder farmers and it is a cash crop in the Great Lakes Region of East Africa (Batte et al., 2019; Dotto et al., 2018). Generally, CROPWAT 8.0 model has been used for calculating banana crop water requirements and irrigation scheduling (Davis et al., 2019; El-Marsafawy et al., 2018; Nithya, 2015; Sabiiti et al., 2016; Surendran et al., 2015), CROPWAT 8.0 was not used to predict yield and its performance to predict yield was not evaluated. Limited research has been conducted on the efficacy of CROPWAT 8.0 to simulate the yield of banana. In agricultural research, comparison of model-based and measured values is important to assess model's accuracy. This evaluation is also key because it can lead to a well-defined range of conditions with which a model is applicable and consistent (Gauch et al., 2003). In anticipation to get a solution to water use efficiency for the benefit of various banana stakeholders, a study was conducted on East Africa Highland Banana (*Musa* spp. AAA-EAHB), a dominant grown group, representing 80% of the cultivars in the region (Taulya, 2015). Within the EAHB group, Ng'ombe cultivar was selected for this study because it is among the preferred cultivars by farmers. The objective of this study was to evaluate the performance of CROPWAT 8.0 model in simulating yield of East Africa Highland banana cv Ng'ombe under deficit irrigation and different irrigation intervals.

2 Materials and Methods

CROPWAT 8.0 is the latest and updated software of earlier versions developed by FAO (1992). This computer programme utilizes monthly climatic data, including temperature, relative humidity, wind speed, sunshine hours and rainfall to calculate the reference evapotranspiration (ET_o) (Naik et al., 2015; Grieser et al., 2006). Key functions of CROPWAT 8.0 include calculations of: (i) the reference evapotranspiration of crops; (ii) crop water requirements; (iii) effective rainfall and irrigation requirements; (iv) water supply for an irrigation scheme of more than one crop (up to 20 crops), and (v) daily water balance computations (Smith, 2000). CROPWAT 8.0 model requires input of crop data (duration of growth stages, crop factors (K_c), rooting depth, allowable soil moisture depletion and yield response factor) to calculate the crop water requirements (*CWR*) on a 10-day period basis. The reference evapotranspiration (ET_o) is calculated using Penman–Monteith method recommended by FAO (Naik et al., 2015). Crop water and irrigation requirements can be predicted by CROPWAT 8.0 for several different agro-climatic zones since CROPWAT 8.0 can easily import and use the database of the New_LocClim software, a local climate estimator of FAO. The latter is a climatic database of over 30,000 stations distributed across the world (Grieser et al., 2006). The first step in the CROPWAT software is to estimate the crop evapotranspiration (ET_c) on a 10-day basis as:

$$ET_c = ET_o \times K_c \tag{1}$$

where, ET_c = actual evapotranspiration by the crop (mm d^{-1}), ET_o = reference evapotranspiration (mm d^{-1}), and Kc = crop coefficient at a specific growth stage.

Monthly climate data, during the study period (18 months), required for calculation of evapotranspiration were provided by New_LocClim software. Those data are minimum and maximum temperature, humidity, wind speed and sun hours (Grieser et al., 2006). Rainfall data were not considered because irrigation water was supplied only through irrigation. Banana crop data included crop coefficients, duration of growth stages, allowable critical soil moisture depletion and yield response factor (Allen et al., 1989; Doorenbos et al., 1980). Considered soil data were: total available water (Difference of field capacity and permanent wilting point), maximum infiltration rate (mm d^{-1}), maximum rooting depth (m) and initial soil moisture depletion as a percentage of total available water (*TAW*).

To evaluate the model's efficiency in estimation of EAHB yield, an experiment was set up at the Kenya Agricultural and Livestock Research Organization (KALRO), Kisii Centre located at 0°41′1.1″S, 34°47′15.2″E. The agroecological zone is Upper midland2 (UM2) with well-drained soils of clay loam (Jaetzold et al., 2006).

Determination of soil properties was done according to Sharma and Yadav (2008) and Kadam and Shinde (2005) and the quality of water for irrigation tested (Singh et al., 1999). Tissue culture seedlings of banana cv Ng'ombe were planted in a rain shelter at a spacing of 3 m × 3 m. The rain shelter was designed in such a way as to isolate the rain shelter from moisture transfer to and from the outside while allowing for equilibration of other weather parameters. To prevent lateral moisture movement from and to the soil outside the rain shelter, a thick polythene sheet (200 × 10^{-6} m), extending from the soil surface to a depth of 120 cm was installed around the entire perimeter of the rain shelter. Crop management practices followed the recommendations proposed by Onyango et al. (2015) and Tushemereirwe et al. (2000). Irrigation water was delivered by a complete trickle irrigation system. Three irrigation levels (80% of ET_c, 90% of ET_c and 100% of ET_c) were combined with three levels of irrigation intervals (4 days, 6 days and 8 days) and coded as IL100.D4, IL90.D4, IL80.D4, IL100.D6, IL90.D6, IL80.D6, IL100.D8, IL90.D8 and IL80.D8. A randomized complete block design (RCBD) with three replications was used and each experimental unit was made up of two plants. Soil samples' analysis showed that the permanent wilting point (*PWP*) was 315 mm m^{-1} and the field capacity at 420 mm m^{-1}. The soil texture was clay with an infiltration rate of 96 mm d^{-1} and the initial soil moisture depletion was at 17% of total available water (402 mm m^{-1}). Table 1 shows the results of the analysis of irrigation water.

Table 1. Irrigation water test results

Parameter	Results	Levels
pH	6.30	Medium
ECw (µS m^{-1})	141.1	Medium
Iron (mg L^{-1})	2.33	High
Manganese (mg L^{-1})	Nil	Low
Calcium (mg L^{-1})	9.57	Low
Magnesium (mg L^{-1})	3.67	Low
Sodium (mg L^{-1})	27.09	Medium
Potassium (mg L^{-1})	8.06	Low
Copper (ppm)	Nil	Low
Total hardness (mg L^{-1})	30	Low
Total Alkalinity (mg L^{-1})	72	Medium
Chloride (mg L^{-1})	3.0	Low
TDS (mg L^{-1})	70	Medium
SAR †	10.53	Slightly High

† SAR = Sodium absorption ratio

Banana water requirements were calculated by CROPWAT 8.0 and applied with respect to different treatments. The amount of water applied at different irrigation intervals was 1370 mm, 1534 mm and 1701 mm at 80%, 90% and 100% of ET_c, respectively. Before running the model, banana crop and soil data were used for model calibration. The crop coefficients at different growth stages were provided and adjusted according to Allen et al. (1989) because of the change in relative humidity and wind speed of the site. K_c values changed from 0.5 to 0.93 at initial and mid-season stages in the first year and increased to a constant value of 1.05 in the second year because of the water requirement of the ratoon plant (Fig. 1).

Bunch weight data per plant were collected at harvest and the yield per hectare was calculated. We compared observed and predicted banana yield at different treatments using standard statistical techniques including mean squared deviation (MSD) which has three components squared bias (SB), squared difference between predicted and observed standard deviations (SDSD) and lack of positive correlation weighted by the standard deviations of predicted and observed values (LCS). SB indicates the agreement between the predicted and observed means, whereas SDSD and LCS together show how closely the model predicts variability (Sapak et al., 2017; Kobayashi and Salam, 2000). Other statistical analyses included Nash and Sutcliffe model efficiency (NSE) (Equation 2) (Phogat et al., 2016).

$$NSE = 1 - \frac{\sum_{i=1}^{n} (M_i - S_i)^2}{\sum_{i=1}^{n} (M_i - \overline{M})^2} \quad (2)$$

where, M_i, S_i, and $\overline{M}$ designate measured yield (t ha^{-1}), simulated yield (t ha^{-1}), and the arithmetic mean of the measured yield (t ha^{-1}), respectively.

The coefficient of determination (R^2) (Phogat et al., 2016; Anache et al., 2016; Zhong and Dutta, 2015; Tabrizi et al., 2012) and paired t-test (Urbano et al., 2019) of SAS version 9.2 (SAS, 2010) have also been used to evaluate the model.

3 Results and Discussion

The water was suitable for irrigation because the parameters values were within the acceptable range. Table 1 shows that the pH of the sample, alkalinity levels and Sodium Adsorption Ratio (SAR) were within the standard range according to Singh et al. (1999). Min et al. (2016) indicated that poor irrigation water quality has adverse effects on soil physicochemical properties, biological processes and affects negatively growth and yields of crops. Table 2 shows measured and simulated values. Comparison of predicted and observed yield showed a high coefficient of determination (R^2 = 0.82) (Fig. 2) and the results of student's t-test revealed that observed yield (38.4 ± 2.37) t ha^{-1}, was not significantly (p≥0.05) different from predicted yield (39.1 ± 2.66) t ha^{-1}.

Table 2. Observed and predicted yields at different treatments

Treatment	Observed yield (t ha^{-1})	Predicted yield (t ha^{-1})
IL80.D4	33.4 de	39.4
IL90.D4	50.6 a	45.2
IL100.D4	51.2 a	51.2
IL80.D6	31.9 e	32.8
IL90.D6	42.1 b	37.7
IL100.D6	42.6 b	42.6
IL80.D8	28.8 f	28.2
IL90.D8	35.5 cd	32.3
IL100.D8	36.6 c	36.6

The MSD analysis between the model's prediction and field observation using squared bias (SB), squared difference between predicted and observed standard deviations (SDSD) and lack of positive correlation weighted by the standard deviations (LCS) showed that CROPWAT 8.0 model's predictions were better at 8 days irrigation interval with a lower MSD of 3.53 t ha^{-1} (Fig. 3). Sapak et al. (2017) indicated that the lower the value of MSD, the closer the predicted value is to the observed one. Compared to other irrigation intervals, 4 days irrigation interval had a higher SDSD, indicating that the model simulated poorly the magnitude of fluctuation between the observed and simulated data. The model calculated yield reduction caused by deficit irrigation, with satisfaction, which makes this model a useful tool for irrigation planning in banana. The average of predicted yield reduction by CROPWAT 8.0 model was found to be 23.2% at 80% of Evapotranspiration (ET_c) and 11.6% at 90% of ET_c at different irrigation intervals. The Nash and Sutcliffe model efficiency (NSE) of 0.81 was calculated, as Zhong and Dutta (2015) indicated the closer the NSE is to 1 the better the prediction is. There were some differences between the actual and predicted yields, implying that some of the biological and environmental processes could not be accounted for by the model. The variability of observed banana yield in this study is attributed to changing levels of irrigation water, irrigation interval and their interactions. The top yield was recorded at IL100.D4 though this yield level was not statistically different from the yield at IL90.D4. Banana plants which received water every 4 days had the best yield and yield components, followed by those of 6 days and finally 8 days. This indicates that more frequent irrigations resulted in better crop performance under deficit irrigation. Similar results were obtained by Aba and Baiyeri (2015) and Lahav and Kalmar (1981) who suggested that the reason behind this behaviour could be: low soil temperatures, stimulated shallower rooting and reduced leaching of soil nutrients with frequent irrigation events. Oteng-Darko et al. (2013) indicated that crop models are not capable of giving

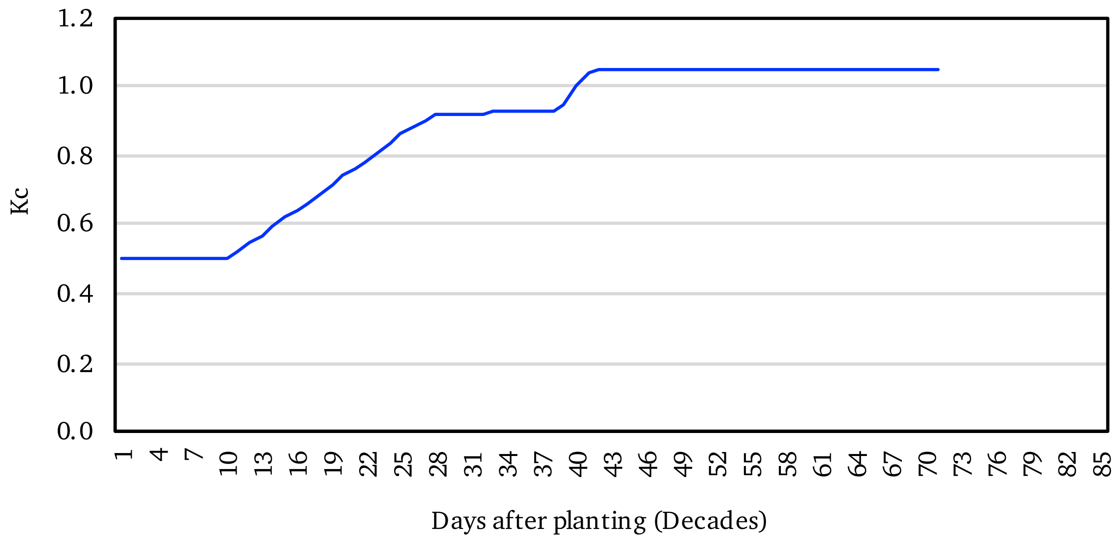

Figure 1. Banana crop coefficients at different growth stages

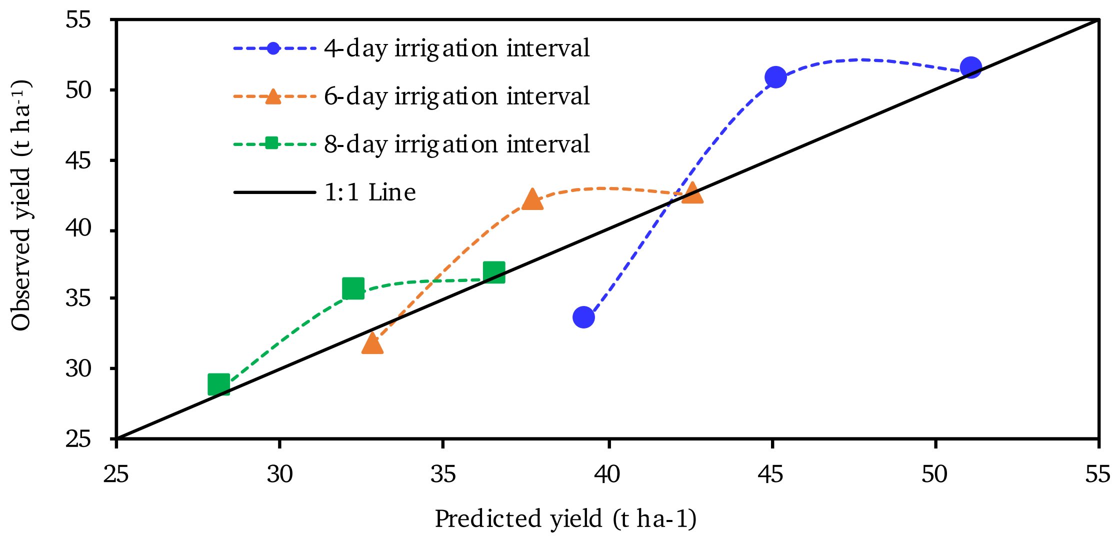

Figure 2. Comparison of Predicted and Observed banana yield. The 1:1 line shows no Significant difference (P > 0.05) between predicted and observed values (R^2 = 0.82)

exact predictions due to insufficient understanding of natural processes and computer programmes' limits. Vozhehova et al. (2018) suggested that CROPWAT 8.0 model application should be used with proper calibration and adjustment of the crop coefficients.

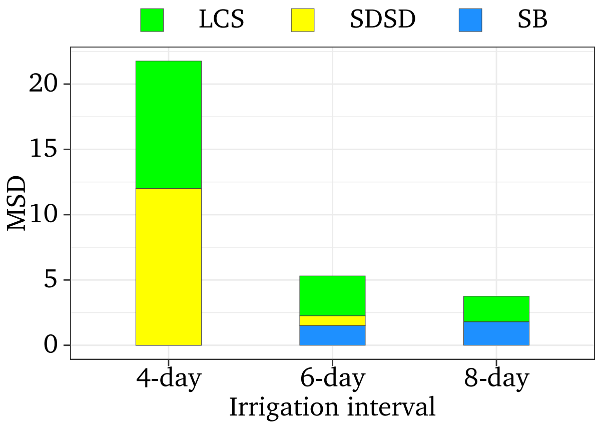

Figure 3. Mean squared deviation and its components. Squared bias (SB), squared difference between standard deviation (SDSD), and lack of correlation weighted by the standard deviations (LCS) -comparing simulated and observed banana yield

4 Conclusions

The calibration of CROPWAT 8.0 model using adjusted crop coefficients for the different growth stages provided a good prediction of the yield of East Africa Highland Banana crop at various levels of irrigation water supply and irrigation intervals. The model was more accurate at 8 days irrigation interval, compared to other irrigation intervals. Further studies are needed to confirm the range of irrigation interval in which CROPWAT 8.0 would be enough reliable to predict the East Africa Highland banana yield. Statistical tests indicated that CROPWAT 8.0 is a reliable model for estimating yield reduction under water deficit conditions and different irrigation intervals.

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Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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