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Field experimentation based simulation of yield response of maize crop to deficit irrigation using AquaCrop model, Arba Minch, Ethiopia

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This experiment was conducted during February to June 2012 in Demonstration farm of Arba Minch University located in the central rift valley of Ethiopia. The aim was to investigate the effects of different levels of deficit irrigation imposed at different growth stages of maize (BH-140) crop on its development, grain yield and water use efficiency. AquaCrop model was calibrated and validated using field experimentation data. The crop water requirement of maize for full irrigation application was calculated using CropWat 8.0. The water application levels considered were 100% of crop evapotranspiration (ETc), 75%ETc, 50%ETc and 25%ETc. based on these irrigation levels and four growth stages of maize crop, ten treatments were arranged. These treatments were replicated three times. Data collected during the experiment were: crop biomass, soil moisture content, irrigation depths and final yield. The result showed that the highest yield was found in treatment six, T6 (8842 Kg/ha) which was subjected to water deficit during mid- and maturity-stages; whereas minimum yield of about 5264 kg/ha was obtained under T8 which was irrigated imposed to deficit during the whole growing season except during the initial stage. The highest (2.11 kg/m^3) and lowest (0.93 kg/m^3) water use efficiency was recorded under T8 and T4. Generally, water deficit of 50%ETc during third and fourth growth stages had no significant effect on the grain yield of maize and it is worthwhile to save irrigation water during these growth stages. The model performed well in simulating the growth of aboveground biomass, grain yield, and canopy cover (CC) for most of the treatments but it was less satisfactory in simulating the growth performance of treatments under prolonged water-deficit. The fact that the AquaCrop model is easy to use, requires less input data, and its sufficient degree of simulation accuracy make it a valuable tool for estimating crop productivity under deficit irrigation, and on-farm water management for improving the efficiency of water use in agriculture.

Key words: Deficit irrigation, growth stage, maize, crop water productivity, AquaCrop.

INTRODUCTION

Globally, irrigated agriculture is the dominate user of fresh water. Water is becoming scarce and hence irrigation water supplies are decreasing in many areas of the world. Climate change predictions of increase in

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temperature and decrease in rainfall mean water will become increasingly scarce.

Generally, Ethiopia is considered as water abundant country. However, water availability for crop production is highly erratic both in space and time. Where in some areas, there is substantial rainfall and surface runoff during some months of the year while in others; there are high dry spell periods (Awulachew et al., 2007). This calls for storage of excess rainfall and runoff that can be utilized during the dry season. Efforts to ensure food self-sufficiency at house-hold level requires efficient use of the stored water and appropriate water application technologies that can be adopted for small-scale irrigation development. The traditional irrigation development paradigm is aiming at supplying sufficient water to crops to avoid water stress during the whole growing stage, so as to achieve maximum yields (Doorenbos and Pruit, 1992). However, the limitations in water availability oblige to adopt alternative irrigation schedules with different frequencies of irrigation to cope with the water scarcity. Because of water availability constraints in most areas of the world, the above paradigm is changing (English et al., 2002) and quite often, the allocation of irrigation water to field is below maximum crop water requirement for maximum yield (Lorite et al., 2007).

In order to optimize crop yields and water use efficiency in irrigated environments, irrigations should be timed in a way that non-productive soil water evapotranspiration and drainage losses are minimized, and possible inevitable water deficits coincide with least sensitive growth period. Therefore, it is critical that conservative irrigation water management practices has to be implemented in order to optimize crop yield by employing deficit irrigation principles that provide a means of conserving irrigation water while maintaining reasonable yield level. Deficit irrigation scheduling practice is the technique of withholding, or reducing the amount of water applied per irrigation at some stages of the crop growth with the aim of saving water, labor, and in some cases energy. This practice does lead to some degree of moisture stress on the crop and reduction in crop yield (Smith and Munoz, 2002). However, when the moisture stress is not severe, the adverse effect on crop yield is minimal and there can be an appreciable increase in crop water use efficiency especially when there is reduction in water losses due to evaporation, deep percolation and runoff (Panda et al., 2004). Furthermore, it is important to determine the crop water production functions that relate crop yield to evapotranspiration (crop yield response to different amounts of irrigation water applied) which shed light on physiological and agronomic response of crops to different levels of water applications (Kipkorir et al., 2001).

Ethiopia is among the major maize producers in Sub Saharan African countries, where smallholder farmers dominate the major share of production. Though maize is widely grown in Ethiopia, only three regional states contribute to 94% of the total annual production. These regions are Oromia, Amhara and Southern Nations, Nationalities, and People's Region (SNNP). According to a five years (2003/2004 - 2007/2008) Central Statics Agency of Ethiopia (CSAE) data, the share of Oromia region was on the average, 60% of the total maize production in the country. This was followed by Amhara region with 21.67% and SNNP region with 12.55%.

Traditionally, maize is consumed in many different food types such as Fososiye, Kurfufa, Kita, Injera, Genfo, and also consumed in the form of homemade drinks such as Bordie and Tella. Its straw is also used for animal feed. Despite its importance, the productivity remains poor with a national average yield of 1.5 tons ha^{-1} (CSAE, 2009).

In recent years, studies that have been conducted on crop yield response to water stress and water use efficiency have shown that deficit irrigation can increase crop yield by improving soil water conditions and their WUE significantly (Doorenbos and Kassam, 1979).

Some of these studies have used crop production functions to determine the irrigation level that maximizes economic return. On the other hand, simulation models are attractive tools to develop irrigation strategies under water deficit conditions, and to obtain reliable yield estimates for field crops that can be expected under various environmental conditions. Some of the models are intended to provide guidelines to mainly a practitioner type of end-user such as people working for extension services, governmental agencies, and various kinds of farmers associations. With good models, realistic estimations of crop yield can be simulated for various environmental conditions. The models are valuable for out-scaling the experimental findings to new environments. Therefore, use of simulation models could help in evaluating the interaction between numerous factors that affect plant growth.

The main objective of this study was therefore, to investigate the effects of different levels of deficit irrigation imposed at different growth stages of maize crop on its development, grain yield and water use efficiency. The specific objectives of the study were:

i. To evaluate the effects of different irrigation water application levels on crops yield and water use efficiency at different crop growth stages.
ii. To calibrate and validate the AquaCrop model using the data generated during the experiment and evaluate its applicability for deficit irrigation management.

MATERIALS AND METHODS

Description of the study area

The field experiment was conducted in the south western zone of SNNP regional state at the Demo-farm of Arba Minch located 500 km south of Addis Ababa during the period of February to June,

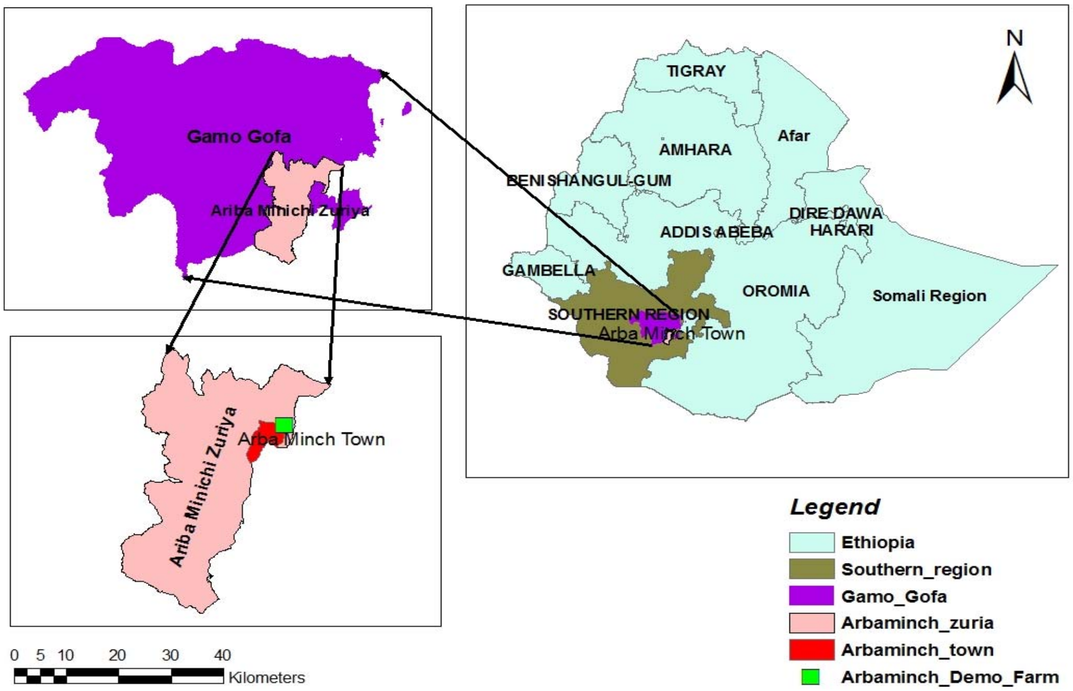

Figure 1. Location map of the study area.

2012. Arba Minch University (AMU) demonstration site was set as a practical illustration for irrigation and drainage related teaching and research purposes right after the establishment of the Arba Minch Water Technology Institute (AWTI) in 1986.

The study area is situated at 37° 34‘ E longitude and 6° 04‘ N latitude, and at an altitude of 1203 m. a.s.l (Figure 1). Mean annual rainfall of the study area is about 750 mm. Average maximum and minimum temperature is about 13 and 29.6°C, respectively. The rainfall distribution has a bimodal nature with the first and second rainfall during February to April and June to September, respectively. The soil of the study area is characterized as clay textured with average filed capacity and permanent wilting point of 34.2 and 18.7%, respectively (Table 1).

Soil characteristics of the study area

Soil samples from the study area were collected from each horizon up to 120 cm depth to characterize the soil in terms of physical characteristics such as textural class (soil texture), EC, pH, organic matter, and the average bulk density. The above mentioned soil parameters were analyzed at in the soil laboratory of AMU. Using Hydrometer method and USDA soil textural triangle, the texture of each 30 cm layer was determined as shown in the Table 1 for the total depth of 120 cm and the texture of the whole profile was clay soil. The experimental site had average field capacity (FC) of 34.25% and average permanent welting point (PWP) 18.7% with the average total available water (TAW) 15.5% in volume percentage (Seyoum, 2006).

The soil pH was determined in 1:2.5 soil: water suspension ratio by potentiometric method using glass electrode. The pH of soils was alkaline ranged from 8.1 to 8.3 with an average of 8.2 and it does not show significant difference throughout the profile.

Electrical conductivity was determined in 1:5 soil: water ratio extract using cell electrode and expressed as dS m^{-1} and appropriate temperature conversion factors for correcting conductivity data to standard temperature of 25°C were used. Measured soil salinity was low as indicated by electrical conductivity (EC) values throughout the profile which ranged from 0.058 to 0.060 ds m^{-1}. The highest EC (0.060 dS/m) was recorded in the lower horizon of the soil profile and lowest in the second from the bottom (60 - 90 cm) horizon of the soil profile.

Experimental design

The experiment was conducted in an intensively cultivated area of Arba Minch University demonstration site. It was designed to expose maize crop (BH-140) to water deficit during one or more of its growing stages. The treatments were watered at the levels of: 100, 75, 50 and 25%ETc to that of the total crop water requirement during four growing stages of the selected crop by considering four growing stages of the crop (Allen et al., 1998) there were ten treatments as indicated in Table 2.

In order to illustrate the impacts of water deficit on yield and some agronomic characteristics of maize, a study was conducted as randomized complete blocks design (RCBD) and three replications to yield a total of 30 experimental plots. The size of each experimental plot was 5 × 4 m. The space between plots and replications were 1.50 and 2 m, respectively. The BH-140 hybrid of maize was selected for the study and it was planted with 40 cm between plant and 80 cm raw spacing. This crop variety was selected for its good adaptability and most usable in the study area. The growing season of the crop was mainly divided into four major growth periods: initial, development, flowering and maturity stages based.

Each plot had five furrows for irrigation water application and five planting rows. The furrows were regularly maintained to sustain their water storage capacities over the season. These treatments were arranged in a way that a single treatment was not subjected to

Table 1. soil physical and chemical properties for the experimental site.

Soil depth (cm)	Type of analysis										
	Bulk density (gm/cm^3)	EC (ds/m)	pH	% Sand	% silt	% Clay	Texture	Organic Matter %	FC Vol. %	PWP Vol. %	TAW Vol. %
0 - 30	1.2	0.059	8.3	20.7	12.0	67.3	Clay	13.0	39.3	21.3	18.0
30 - 60	1.2	0.059	8.1	14.0	34.7	51.3	Clay	13.9	34.7	19.7	15.0
60 - 90	1.3	0.058	8.3	16.7	26.0	57.3	Clay	12.6	31.6	17.0	14.6
90 - 120	1.1	0.060	8.1	20.7	20.0	59.3	Clay	12.4	31.4	16.8	14.6
Average	1.2	0.059	8.2	18.0	23.2	58.8	Clay	13.0	34.25	18.7	15.55

Table 2. Total number of treatment combinations over crop growing stages.

Treatment	Crop growing stages/Level of water application in %			
	1	2	3	4
T1	100	100	100	100
T2	100	75	75	75
T3	100	100	75	75
T4	100	100	100	75
T5	100	50	50	50
T6	100	100	50	50
T7	100	100	100	50
T8	100	25	25	25
T9	100	100	25	25
T10	100	100	100	25

one level of deficit for the whole growing stage with the exception of control one, T1.

Crop water requirements and irrigation scheduling

The daily crop water requirements were calculated by multiplying the reference evapotranspiration values with the maize crop coefficients (0.3, 0.5, 1.2 and 0.5) initial, development, flowering and maturity stages, respectively given by Allen et al. (1998). The amount of irrigation water required at 10 days interval, number of irrigation events is summarized in Table 3. Fixed interval (every ten days) and variable depth (refill to field capacity) irrigation scheduling technique was selected. Optimal or ‘‘no stress’’ irrigation was calculated using the FAO CROPWAT program as the net amount of irrigation required to refill the soil moisture deficit with weekly application of irrigation water. The depth applied to other treatments was taken simply as percentage of the optimal irrigation at specific growth stage or throughout the growing season.

Agronomic practices and water application

Land preparations was done using labor forces for seedbed preparation and the experiment was conducted during the dry season using irrigation water only (no rainfed) in which shelters were used to exclude rain. Maize (BH-140) cultivar was sown by hand at the end of January and harvested at the end of June of the same year. The 90% seedling emergence was observed about 7 days later. After germination and establishment, thinning was carried out to maintain the spacing between plants to be 40 cm. 12 kg/ha DAP (diammonium phosphate) was applied during sowing period where as 10 kg/ha urea was applied twice during vegetative stage and at the beginning of flowering stage, respectively.

First, the required crop water was calculated using CROPWAT 8.0 computer programme (Allen et al., 1998) on daily basis. Calculations of water and irrigation requirements were done using inputs of climatic, crop and soil data, as well as irrigation and rain data. Daily reference evapotranspiration was calculated from max- and min- temperature, humidity, sunshine/radiation, and wind-speed data, according to the FAO Penman-Monteith method (FAO, 1998). After determining the total irrigation water requirement, the different water application levels (Table 2) to induce water deficits were quantified. Accordingly, the corresponding irrigation amount has supplied to each experimental plot using calibrated siphon tubes through furrow irrigation method and appropriate flow control equipment was used. Water was carefully controlled to avoid the flow of water into water deficit plots. Since the furrows are close ended all water flowing into the furrows were infiltrated over the entire length, that is, there was no runoff. The fact that the furrows are short, the stream size is large and the cut-off time is short, no significant deep percolation will be expected. Soil moisture was determined using gravimetric method by taking soil samples from effective root zone of the crop two days before and after irrigation. To maintain the capacity of furrows constant throughout the growing season, maintenances were done every time before irrigation.

Plots which are to be subjected to water deficit during particular growth stage according to schedule were deprived of irrigation water application and also protected from possible supply of water through rainfall using plastic shelters. The shelters were designed in such a way that they can easily be rolled-up when there is no

Table 3. Amount of irrigation water required for maize in 10 days interval (mm).

	Treatment									
Date	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**
10-Feb	61.1	61.1	61.1	61.1	61.1	61.1	61.1	61.1	61.1	61.1
20-Feb	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7
2-Mar	30.4	22.8	30.4	30.4	15.2	30.4	30.4	7.6	30.4	30.4
12-Mar	36.6	27.5	36.6	36.6	18.3	36.6	36.6	9.2	36.6	36.6
22-Mar	55.5	41.6	55.5	55.5	27.8	55.5	55.5	13.9	55.5	55.5
1-Apr	63.7	47.8	63.7	63.7	31.9	63.7	63.7	15.9	63.7	63.7
11-Apr	68.3	51.2	51.2	68.3	34.2	34.2	68.3	17.1	17.1	68.3
21-Apr	60.1	45.1	45.1	60.1	30.1	30.1	60.1	15.0	15.0	60.1
1-May	55.7	41.8	41.8	55.7	27.9	27.9	55.7	13.9	13.9	55.7
11-May	60.7	45.5	45.5	60.7	30.4	30.4	60.7	15.2	15.2	60.7
21-May	66.1	49.6	49.6	66.1	33.1	33.1	66.1	16.5	16.5	66.1
31-May	61.0	45.8	45.8	45.8	30.5	30.5	30.5	15.3	15.3	15.3
10-Jun	42.6	32.0	32.0	21.3	21.3	21.3	10.7	10.7	10.7	10.7
20-Jun	27.6	20.7	20.7	13.8	13.8	13.8	13.8	6.9	6.9	6.9
26-Jun	0	0	0	0	0	0	0	0	0	0
Total	720.1	563.0	609.6	687.3	406.0	499.1	654.5	248.9	388.5	621.7

rainfall and unrolled when rainfall occurs and during night. At the end of each irrigation application or before the next irrigation leaf area and aboveground biomass were collected by removing one plant per plot.

Crop water productivity

Crop water productivity (WP) or irrigation water use efficiency (IWUE), as reviewed by Molden (2003), is a key term in the evaluation of deficit irrigation (DI) strategies. The water productivity with dimensions of kg/m^3 is defined as the ratio of the mass of grain yield (Ya, kg/ha) to the volume of water consumed by the crop (Eta, mm):

$$WP = \frac{Y_a}{ET_a} \quad (1)$$

Eta refers to water lost both by soil evaporation and by crop transpiration during the crop cycle. Since there is no easy way of separating between these two processes in field experiments, they are generally combined under the term of evapotranspiration (ET) (Allen et al., 1998).

$$ET_C = I + P - D - R_O \pm \Delta S \quad (2)$$

Where I, P, and D are irrigation, precipitation, deep percolation (mm) respectively; Ro is runoff (mm); ΔS is the change in soil moisture storage between soil moisture measurements (mm).

Crop parameters and measurements

The days from sowing to emergence, maximum canopy cover, start of senescence, and physiological maturity, as well as maximum rooting depth were recorded in the field. The base and upper temperatures were assumed to be 10 and 30°C, respectively. Root observation was done in the field at about maximum canopy cover and at maturity from all plots. Leaf length, L (cm) and leaf width, W (cm) of plants from each treatment was measured using tape meter at 10-day intervals throughout the growing season.

The total leaf area A (cm^2) for maize leaves was therefore obtained with the relationship (Kang et al., 2003):

$$A = 0.759 \sum_{i=1}^{m} L_i \times W_i \quad (3)$$

The LAI was obtained by the ratio of total leaf area of per unit ground area:

$$LAI = \frac{\text{Measured leaf area per plant}(cm^2)}{100 \times 100 cm^2} \times \frac{\text{number of plants}}{m^2} \quad (4)$$

AquaCrop simulates transpiration in terms of canopy cover (CC) of the crop, but often experimental studies measure LAI but not canopy cover. Therefore, canopy cover was estimated from leaf area index based on Hsiao et al. (2009).

$$CC = 1.005 \times \left[1 - \exp\left(-0.6\, LAI\right)\right]^{1.2} \quad (5)$$

Where CC (%) is canopy cover and LAI is leaf area index.

An empirical relationship between CC and LAI of maize was obtained by regression, plus slight adjustments at the extreme low and high end of CC values.

Data collection and analysis

All relevant data including weather conditions, soil and crop characteristics (such as open air dried aboveground biomass and yield, leaf area), and amount and timing of irrigation have been collected from the experimental plots and analysis was made to identify optimal deficit irrigation management practices based on crop yield responses and water use efficiency. For this purpose JMP5, GenStat 12th Edition softwares were used. Weight of seeds of each plot from the three middle furrows was recorded. One plant per plot was uprooted before the next irrigation and dried in open air and weighed after chopping it into pieces.

The open air dried grain yield and above ground dry biomass weight was measured at 13% moisture content. The data collected were subjected to descriptive statistical analysis and ANOVA test to see the effects of different treatments on the yield and water use efficiency. The results are presented in the form of tables and figures.

Model performance evaluation

The performance of the model was evaluated using the following statistical parameters of the root mean square error (RMSE) calculated as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - S_i)^2} \tag{6}$$

And the model efficiency (ME) (Nash and Sutcliffe, 1970) is calculated as:

$$ME = 1 - \frac{\sum_{i=1}^{N}(O_i - S_i)^2}{\sum_{i=1}^{N}(O_i - \overline{O}_i)^2} \tag{7}$$

Where Si and Oi are the simulated and observed (measured) values as samples taken along the season (e.g., biomass and CC), or at the end of the season (e.g., grain yield), N is the number of observations, and $\overline{O}_i$ is the mean value of O_i. ME ranges from negative infinity to Positive 1; the closer to 1, the more robust the model.

The RMSE in Equation 6 represents a measure of the overall, or mean, deviation between observed and simulated values, that is, a synthetic indicator of the absolute model uncertainty. In fact, 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.

Sensitivity analysis

Before applying a model, it is necessary to have some familiarity with its behavior and sensitivity to input parameters. Sensitivity analysis helps to recognize the parameters that have significant impact on model output.

To assess the robustness of the AquaCrop model for maize crop under Arbaminch condition and the required quality of the input data, a sensitivity analysis was worked out by altering inputs and by keeping some inputs constant such as normalized water productivity (WP* = 32 for C4 crops), Temperature (base temperature = 10 and upper temperature = 30). The inputs for sensitivity analysis for this research were agronomic data, soil, meteorology, and irrigation management data. In order to compare the model outputs, the inputs were changed by trial and error in each step. After changing the values of input parameters, the model outputs were compared with the observed data. The results showed that the most sensitive agronomic parameter in AquaCrop model were time to senescence, reference harvest index (HIo), canopy development, canopy decline. However, the model showed less sensitive to time of seed emergence, length of flowering period, days to flowering. The difference in simulated above ground biomass and grain yield was used for the assessment. In general, the most sensitive parameters were those which are cultivar specific parameters (with white cell box) and less sensitive parameters are those with silver cell box in the model.

RESULTS AND DISCUSSION

Yield, biomass, and water use efficiency

The result in Table 4 indicated that yield of maize was significantly ($p < 0.05$) affected by the deficit irrigation. The highest yield was found in T6 (8.842 t/ha) which was subjected to water deficit during mid and maturity-stages whereas minimum yield of maize was obtained under T8 (5.264 t/ha) which was deficit during the whole growing season except during the initial stage.

According to the result shown in Table 4 both T2, T3, T6, and T7 are within the yielding potential of the hybrid (BH-140) maize crop yield collected from the research center which is 7.5 to 8.5 t/ha, and the remaining treatment were also in the range of yield collected from the farmer which is 4.7 to 6.0 t/ha (source; Bako Agricultral Mechanization Research Center).

There was significant different between the yield of T6 (8.842 t/ha) and T8 (5.264 t/ha) which was giving 25%Etc during development-, middle-, and late/maturity-stages of the crop growing season. According to the result obtained, giving 25%ETc during development-, middle-, and late/maturity-stages of the crop growing season has affected the yield of maize more as compared to other treatments. Giving 50%ETc of crop water requirement during middle- and maturity-stages were better than giving 100%ETc of crop water requirement throughout the growing season.

On the other hand, ANOVA showed that irrigation water use efficiency (IWUE) was significantly different. Thus, T8 (2.11 kg/m^3) and T4 (0.93 kg/m^3) had the highest and the lowest irrigation water use efficiency, respectively. This result elaborated that applying 25%ETc of crop water requirement during development-, mid-, and late /maturity-stages of the crop growing season has better water use efficiency than applying optimal irrigation with (100%ETc) crop water requirement.

As indicated in Table 4, T6 had the highest and T8 the lowest yield. From the treatments, highest amount of water was saved in T8 (65%) and 5% of water was saved in T4 taking into account T1 as a control (crop water requirement base). The amount of water saved in T6 was 31% which is higher than the other six treatments (T1, T2, T3, T4, T7, and T10). When the treatments are compared in terms of yield reduction/increase, T6 had (-23%) which shows there is no yield reduction rather 23%

Table 4. The amount of water saved and yield reduction.

Treatment	Irrigation (m^3/ha)	Yield (kg/ha)	IWUE (kg/m^3)	Water saved (%)	Yield Reduction (%)	Above ground dry biomass (t/ha)	HI (-)
T1	7201	7212	1.01	0	0	13.385	0.539
T2	5630	7576	1.35	22	-5	11.827	0.641
T3	6096	8088	1.33	15	-12	12.202	0.663
T4	6873	6418	0.93	5	11	12.723	0.504
T5	4060	6189	1.52	44	14	10.394	0.595
T6	4991	8842	1.77	31	-23	10.484	0.843
T7	6545	8369	1.28	9	-16	11.675	0.717
T8	2489	5264	2.11	65	27	8.862	0.594
T9	388.5	5929	1.53	46	18	9.327	0.636
T10	621.7	6736	1.08	14	7	10.290	0.655

yield increase compare to the control treatment (T1) and T8 (27%) the highest yield reduction since T1 is considered as control.

The grain yield and aboveground dry-biomass of the maize plant is presented in Table 4. ANOVA test showed that there is a significant difference between treatments in terms of grain yield and total aboveground dry-biomass. It shows that there is no significant difference between Treatments T1, T3, T4, and T7 in terms of aboveground dry-biomass.

The harvest index (HI) which refers to the percentage dry matter allocated to grain yield, increasing with increasing magnitude of deficit from all except under T6. The lowest HI is 0.504 and the highest is 0.84. These values are relatively higher than the values of 0.31 - 0.55 reported by Farre and Faci (2009) as cited by Mekonen (2011).

Simulation using AquaCrop model

Model calibration and validation

The model has been calibrated based on the measured crop data of all the treatments. The main calibration parameters for CC include the canopy growth coefficient (CGC), the canopy decline coefficient (CDC), water stress (P_{upper}, P_{lower} and the shape factor) affecting leaf expansion and early senescence. Canopy cover per seedling was estimated based on the general knowledge of the crop characteristics by specifying row spacing and plant spacing. Then, simulation was done for the above crop phenologies and the results were compared with the measured values.

In the model, initial canopy cover (CCo) was estimated based on the data from agronomic practice from row planting, row spacing (0.80 m) and plant spacing (0.40 m). Hence, the estimated initial canopy cover (CCo) for the given maize crop has been found 0.16% (3.1 plants/m^2 or 31, 250 plants/ha).

To estimate the canopy expansion rate, phonological data (listed in Table 5) such as dates to emergence, maximum canopy cover, senescence and maturity were used. The model resulted fast canopy expansion and moderate canopy decline. The canopy growth coefficient (CGC) and canopy decline coefficient (CDC) were 1.46%/°C/day and 0.114% /°C/day, respectively.

The crop parameters used for calibrating the model are presented in Tables 5 and 6. Table 5 shows maize phenological development. Table 6 shows the different crop parameters and the values used for calibrating the model. Stress parameters such as canopy expansion and canopy senescence coefficients were adjusted and re-adjusted to simulate the measured canopy cover.

The simulated above ground dry biomass agreed well with the observed biomass (Figure 3). There was strong relationship between the observed and simulated biomass (R^2 > 0.85). Table 7 shows a deviation of the simulated grain yield and above ground dry biomass from their corresponding observed data. The deviation of the simulated above ground dry biomass from the observed data for both T5 (69.23%) and T8 (84.39%) shows there was over estimated of above ground dry biomass by the model. Whereas the deviations of the simulated grain yield from the observed data for both T5 (-35.72%) and T8 (-94.96%) shows there was under estimation of grain yield of maize crop by the model. Although not largely different, the aboveground dry biomass was better simulated by the model when compared with the grain yield which is in line with Araya (2010b).

Both grain yield and above ground dry biomass were adequately simulated by the model. The simulated grain yield (Figure 4) and above ground dry biomass (Figure 5) agreed well with their observed grain yield and above ground dry biomass except for both T5 and T8 which was consecutively subjected to water deficit from development to maturity stages. There was strong relationship between the observed and simulated above

Table 5. Phenological observations of Maize crop (BH 140) from the study area (maximum rooting depth in 1.80 m).

Growth parameter	Days
Sowing to emergence	7
Sowing to flowering	68
Sowing to start of senescence	110
Sowing to max canopy cover	68
Sowing to max rooting depth	110
Sowing to harvesting	147

Table 6. Crop data input used in AquaCrop to simulate maize.

Description	Value	Units	Interpretation
Canopy cover per seedling at 90% emergence (CCo)	0.16	%	Increase in CC relative to existing CC. (3.1 cm^2 per plant)
Canopy growth coefficient (CGC)	1.46	%/°C/day	Increase in CC relative to existing CC per GDD
Maximum canopy cover (CCx)	90	%	well covered
Maximum crop coefficient	1.25	-	At max canopy
Canopy decline coefficient (CDC) at senescence	1.14	%/°C/day	Decrease in CC relative to CCx per GDD
Water productivity	32	g/m^2	Biomass per m^2
Upper threshold for canopy expansion	0.20	-	Leaf growth stop completely at this P value
lower threshold for canopy expansion (P_{lower})	0.55	-	Above this leaf growth is inhibited
Leaf expansion stress coefficient curve shape	3.1	-	
Upper threshold for stomatal closure	0.55	-	Moderately tolerant to water stress but above this stomata begins to close
Stomata stress coefficient curve shape	3.1	-	
Canopy senescence stress coefficient (Pupper)	0.55	-	Above this canopy senescence begins
Senescence stress coefficient curve shape	3.1	-	
Reference harvest index (HIo)	70	-	Common for good condition
Coefficient, HI increased by inhibition of leaf growth at flowering	0.85	-	Upper threshold for increase in HI due to inhibition of leaf growth
Coefficient, HI increased due to inhibition of leaf growth before flowering	12	%	Maximum HI increased by inhibition of leaf growth before flowering
Coefficient, HI decreased due to water stress affecting stomata closure during yield formation	5	-	Moderate
Coefficient, HI increased due to water stress affecting leaf expansion during yield formation	2	-	Moderate

As shown in Figure 2 the simulated and observed canopy cover was well correlated with strong relationship ($R^2 > 0.80$).

ground biomass and grain yield ($R^2 > 0.91$).

Model performance evaluation

The model efficiency (ME) and root mean square of error (RMSE) was used to evaluate the model performance. These parameters showed good to moderate performance for above ground dry biomass (ME = 0.99, RMSE = 0.81 t/ha) and grain yield (ME = 0.97, RMSE = 1.25 t/ha). Model efficiency and mean square error for aboveground dry biomass was done by removing the two most outliers (T5 and T8). According to the validation results, the calculated ME were close to one that is the more the robust the model. Also, moderate RMSE values indicate the good performance of the model.

Conclusions

The advantage of deficit irrigation lies in saving water and

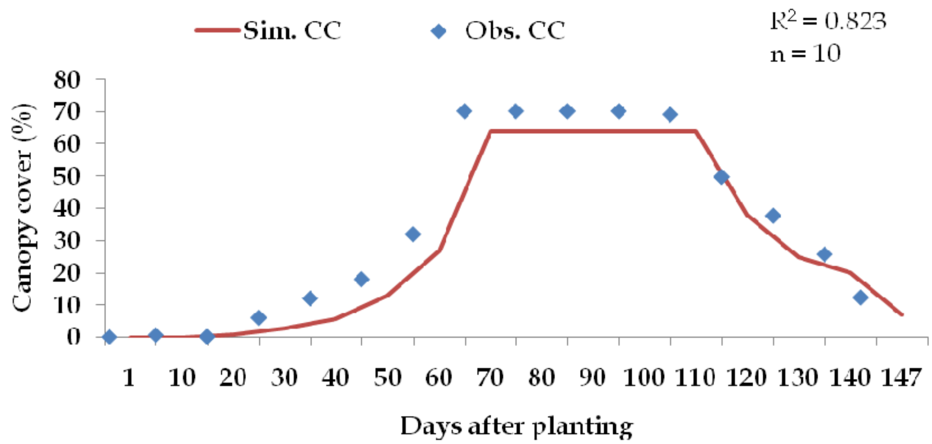

Figure 2. Simulated and observed canopy cover.

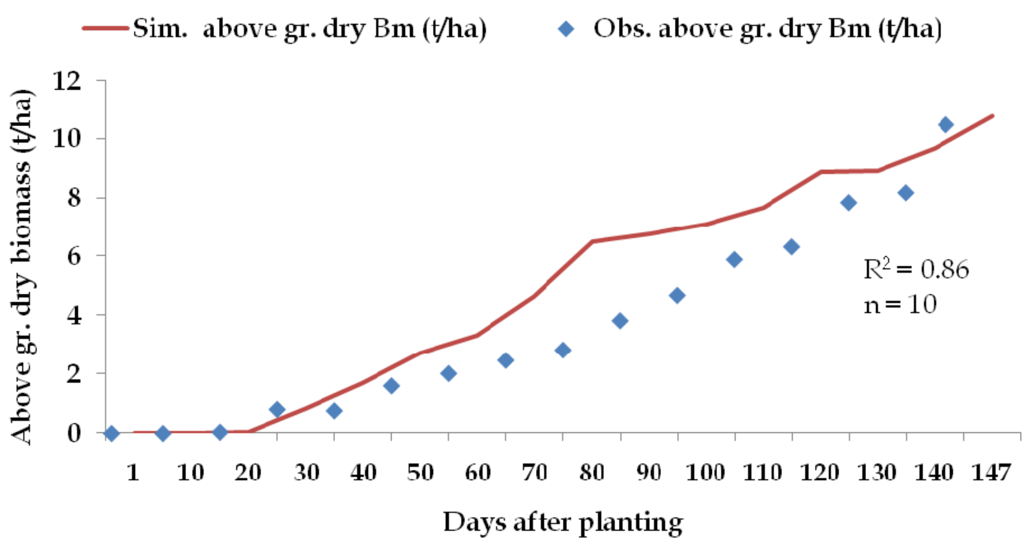

Figure 3. Simulated and observed above ground dry biomass.

Table 7. Simulated and observed grain yield and above ground dry biomass of treatments and % of deviations from observed.

Treatment	Yield			Above ground dry biomass		
	Observed (t/ha)	Simulated (t/ha)	Dev. (%)	Observed (t/ha)	Simulated (t/ha)	Dev. (%)
T1	7.21	7.61	5.23	13.39	14.85	9.87
T2	7.58	8.27	8.39	11.83	12.51	5.46
T3	8.09	9.27	12.75	12.20	12.96	5.85
T4	6.42	7.61	15.66	12.72	13.85	8.14
T5	6.19	4.56	-35.72	10.39	33.78	69.23
T6	8.84	10.27	13.90	10.48	10.78	2.75
T7	8.37	8.34	-0.35	11.68	11.99	2.63
T8	5.26	2.70	-94.96	8.86	56.76	84.39
T9	5.93	6.42	7.65	9.33	9.99	6.64
T10	6.74	7.61	11.48	10.29	10.74	4.19

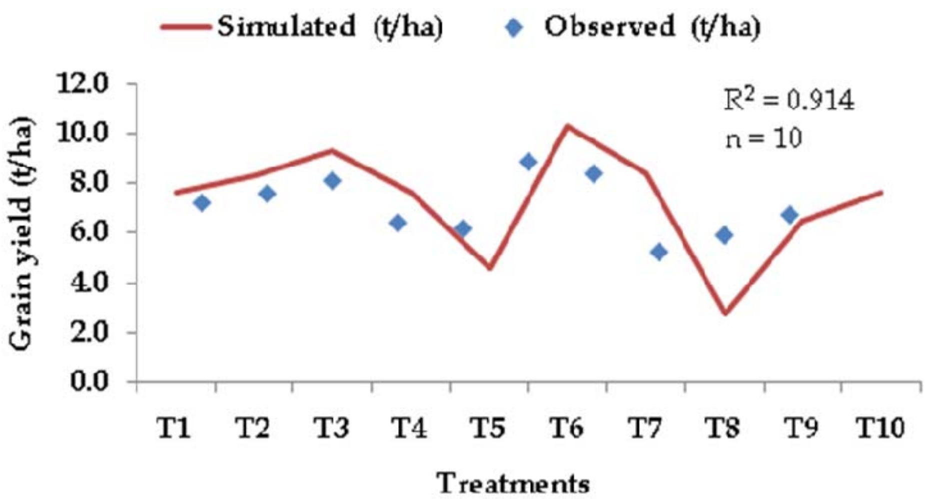

Figure 4. Comparison of simulated and observed grain yield of each treatment.

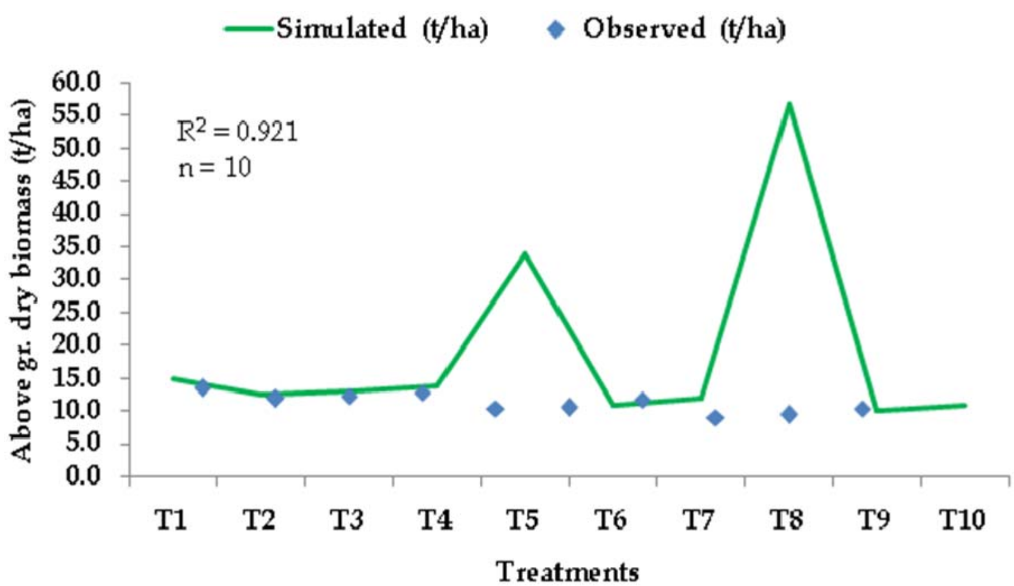

Figure 5. Comparison of simulated and observed above ground dry biomass of each treatment.

increase water productivity while maintaining optimum yield as close to fully irrigated farm (Mekonen, 2011). From the results of the experiment, continuously applied 25% of the total crop water requirement showed more yield reduction. On the other hand, slightly deficit treatments had less yield reductions. However, even 50%ETc water application throughout the growing season except the first stage had significant yield reduction. This indicates that prolonged water deficit below 50% of crop water requirement could significantly affect the yield.

There was no yield reduction observed under treatments which was irrigated 50%ETc during third and forth growth stage, followed by treatments irrigated 75%ETc during first, second, and third growth stages and plot irrigated 25% of crop water requirement only during the last stage. This indicates that water deficit at flowering and harvesting stages up to 50%Etc and only 25%ETc at harvesting stage have not significantly affected the yield. That means with this application, water and other irrigation expenses can be saved. By doing so more land can be irrigated with the saved water to enhance more production.

Generally, full irrigation has not significantly improved the grain and dray biomass yield when compared with their corresponding deficit irrigation treatment. In line with Nagaz et al. (2008) as cited in Araya 2010a obtained the highest yield and biomass at full irrigation (100%ETc) but was not significantly higher than the treatment with mild water stress (above 50%Etc at third and fourth growing stages). Hence, it is possible to generalize that the maize (BH-140) cultivar in our study site has showed positive response to mild water stress condition.

Besides to this, the most sensitive stage of any crop must be investigated to reduce sever yield reduction effects. The knowledge of the most sensitive stages of any crop to water deficit is crucial to manage and apply deficit irrigation technologies. Identifying sensitive growth stages of a particular cultivar under local conditions of climate and soil fertility allows irrigation scheduling for both maximum crop yield and most efficient use of scarce water resources. Hence, we found the most sensitive stage was during the third stage if we irrigate below 50%Etc.

In general, IWUE has increased with decreasing water application which, however is also related to decreased grain yield and hence may not be desirable from the farmers' perspective. Other agricultural inputs need to be appropriately used to enhance productivity by maintaining improved IWUE.

AquaCrop model's calibration and validation is necessary for each crop and in every climate. The results of this research showed that this model is capable of simulating above ground biomass, canopy cover, and grain yield of maize for full supplied irrigation and treatments with some water deficit; but under sever water deficit (25%ETc of full irrigation), and prolonged 50% water stress, the model performed less satisfactorily. According to the validation or model evaluation results, the calculated RMSE and ME values were 0.81 t/ha and 0.99 for grain yield; and 1.25 t/ha and 0.97 for above ground dry biomass, respectively.

RECOMMENDATIONS

The highest yield was found from T6 (8.84 t ha^{-1}) by giving 50% of crop water requirement during the third growth stage which is still better than giving 100% of crop water requirement (full irrigation) throughout the growing season. Therefore, we can recommend that this application of irrigation water (100, 100, 50 and 50%) is best for Arba Minch condition.

AquaCrop version 3.1 has adequately simulated the above ground dry biomass, grain yield, HI, and canopy cover of maize under various irrigation water conditions. There was over estimation of aboveground dry biomass and under estimated of grain yield of maize crop by the model for treatment consequently subjected to water deficit (T5) and for the severely deficit treatment (T8). From this we can recommend that, AquaCrop model is less satisfactory simulating treatments with sever or prolonged water deficit below 50%ETc.

Assuming that water is scarce and land is not scarce, the model has indicated the possibility of obtaining more grain and biomass from relatively larger maize crop by applying less water. This result may contribute to food security improvement through increasing crop yields especially in water deficit areas.

Conflict of Interest

The author(s) have not declared any conflict of interests.

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Abbreviations: °C, Degree celsius; **AMU**, Arba Minch University; **BH**, Bako Hybrid; **CC**, Canopy Cover; **CSA**, Central Statics Agency of Ethiopia; **dS m^{-1}**, deci-Siemen per meter; **EC**, electrical conductivity; **Etc**, crop evapotranspiration; **FAO**, Food and Agriculture Organization; **GDD**, growing degree days; **Kg/ha**, Kilogram per hectare; **kg/m^3**, kilogram per meter cube; **LAI**, Leaf Area Index; **SNNP**, Southern Nations, Nationalities, and People's Region; **t/ha**, tones per hectare; **T1, T2,…, T10**, Treatment one, Treatment two,…, Treatment ten; **USDA**, United States Department of Agriculture.

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