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Application of AquaCrop model for maize under water and nitrogen managements in a humid environment

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ABSTRACT

Globally, it is well debated fact that the water productivity in agriculture needs to be raised in order to meet the increasing demand for the feed and food production, which will double by 2050. Simulation models have been developed for predicting the effects of soil, water and nutrients on growth and water productivity of different crops. In this study, AquaCrop model was calibrated for grain maize (Single Cross 260) using drip irrigation system under varying irrigation and nitrogen levels. The intervals of irrigation were 6 days (F_1), 12 days (F_2) and 18 days (F_3) which combined with different nitrogen levels of 0 (N_1), 120 (N_2), 180 (N_3) and 240 kg ha^{-1}. Root Mean Square Error (RMSE), normalized Root Mean Square Error (RMSE$_n$), Mean Absolute Error (MAE), Prediction error (Pe) and coefficient of determination (R^2) were used to test the model performance. The model was calibrated for simulating maize grain and biomass yield for all treatment levels with the prediction error $0.37<Pe<1.5$ percent, $0.87<R^2<0.92$ and $0.8<RMSE<1.37$ t ha^{-1}. The results of the study showed that the AquaCrop model simulated aboveground biomass and grain yield in normal conditions more accurately than moderate and severe water stress conditions.

INTRODUCTION

Fresh water is an indispensable natural resource, which plays a vital role in the development of any country. Thus, on one hand, failure to develop and implement the technologies to enhance water productivity will result in use of more water in future to sustain the present level of agricultural production and on the other hand, use of water in excess of that required for crop growth will have a significant negative impact on ecosystem and livelihood of the region (FAO 2008). Improving crop water productivity for increasing maize production most importance to obtain more yield per drop with declining irrigation resources. As a result, water allocation has become one of the most vexing problems faced by policy makers. In many water scarce countries, irrigation is the dominant user of water. Water withdrawal for agricultural purposes accounts for about 75 per cent of all usages in developing countries and the FAO has predicted a 14 per cent net increase in use of water to meet the food demands by the year 2030 as compared to year 2000 (FAO 2008). The water-driven crop growth models assume a linear relation between biomass growth rate and transpiration through a water productivity (WP) parameter (Tanner and Sinclair 1983; Steduto and Albrizio 2005). This approach avoids the subdivision into different hierarchical levels, which results in a less complex structure and reduces the number of input parameters (Steduto et al. 2009). One of the major advantages of the water-driven module over radiation-driven is the opportunity to normalize the WP parameter for climate (both the evaporative demand and the atmospheric CO_2 concentration) in the former which, therefore, has a greater applicability in different locations under varying spatio-temporal settings (Steduto and Albrizio 2005; Steduto et al. 2007). Crop models *viz.* CERES-Maize (Jones and Kiniry 1986), WOFOST model, CropSyst (Stockle et al. 2003) and the Hybrid-Maize model (Yang et al., 2004) have been used for prediction of yield of maize crop. Most of these models, however, are quite sophisticated; require advanced modeling skills for their calibration and subsequent operation, and require large number of model input parameters. Some

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models are cultivar-specific and are not easily amenable for general use. In this context, the recently developed FAO AquaCrop model (Raes et al. 2009; Steduto et al. 2009) is a user-friendly and practitioner oriented type of model, because it maintains an optimal balance between accuracy, robustness, and simplicity, and requires a relatively small number of model input parameters. AquaCrop has been parameterized and tested on maize by using experimental data of six cropping seasons in the University of California Davis, USA (Hsiao et al. 2009). Abedinpour et al. (2012) indicated that, the Aquacrop model was more accurate in predicitng the maize yield under full and 75% FC as compared to the rainfed and 50% FC. AquaCrop model required lesser number of inputs data in simulating the maize growth and yield under different water and fertilizer availability scenarios, as compared to other crop models. Teklu et al. (2009) simulated the WP of maize under varying soil fertility scenarios (poor, near optimal and non-limiting) under rainfed conditions using the AquaCrop model in Blue Nile Basin, sub-Saharan Africa. The result indicated that grain yield of maize increased from 2500 kg ha^{-1} under poor to 6400 kg ha^{-1} and 9200 kg ha^{-1} with near optimal and non-limiting soil fertility conditions, respectively.

Therefore, investigation was undertaken to calibrate AquaCrop model for maize grown in humid environment and evaluate its performance under different irrigation intervals and nitrogen scenarios.

MATERIALS AND METHODS

The experimental was conducted in the research field at the agricultural college in Islamic Azad University, Lahijan, Iran, during season of 2012. The research field is located between 52° 36′ E longitude and 29° 33′ N latitude at an average elevation of 2 m above mean sea level. Climate data during the experiment period for use in the model was acquired from the observatories located within the research field. Weather parameters during the experiment are shown in Table 1.

Table 1. Weather parameters during 2012

Year	Month	Avg. Max. Temp. (ºC)	Avg. Min. Temp. (ºC)	Avg. Sunshine (hr day^{-1})	Avg. Rainfall (mm)
2012	June	28.5	22.5	10.7	0
	July	28.15	23	10	0
	Aug.	28.25	19.3	10	0
	Sep.	21	9.8	9.7	0
	Oct.	17.8	4.4	8.5	0.78

Avg.: Average, Temp.: Temperature

The experiment was laid in randomized complete block design (RCBD) with a split plot layout comprised I_1; irrigation interval at 6 days, I_2; irrigation interval at 12 days and I_3; irrigation interval at 18 days. The Nitrogen application levels were no nitrogen, N_1; 120 Kg N ha^{-1}: N_2; 180 Kg N ha^{-1} N_3 and 240 Kg N ha^{-1}: (N_4). There were three furrows in each plot of 8 × 2 m size and the replications were separated by 2 m to ensure that the treatments in plots were independent to each other. The furrows were 75 cm apart with plant spacing of 20cm in each furrow. The maize hybrid Single Cross 260 cultivar was sown on 22th may. Physical and chemical properties of soil and the experiment details are presented in Table 2. Furrow irrigation was used for plants irrigation. Measured amounts of water were applied using a water meter.

The N fertilizer was applied in three split doses with one-third given as basal, one-third at 21 days after sowing (DAS) and the remaining at 42 DAS. The yield was measured at the physiological maturity stage by selecting three middle rows of each experimental plot. After harvesting, the cobs were air dried and grains were separated from the cobs. Further, the grain weight was measured for each plot and the yield per ha was estimated.

Soil moisture content of 15 cm profiles and up to crop root zone were monitored periodically for irrigation scheduling, i.e. deciding the date and quantity of irrigation water during the crop growth period. The date of irrigation was decided when the soil moisture of the root zone reached 50% of the total available water (TAW), i.e. when half the moisture between the field capacity (FC) and permanent wilting point (PWP) gets depleted. The quantity of irrigation water for each treatment was calculated based on the soil moisture content before irrigation and root zone depth of the plant using Eq. 1:

$$SMD= (\theta_{fC}-\theta_i) \times B_d \times D \qquad (1)$$

Where SMD: soil moisture deficit (mm), θ_{fC}: soil water content at field capacity, θ_i: soil water content before irrigation (weight percent basis), D: depth of root development (mm), B_d: bulk density of the particular soil layer (g cm^{-3}).

Canopy development was measured in terms of growth stages, leaf area, root length, and above ground biomass on biweekly basis by removing two plants per plot. Date of emergence, maximum canopy cover (CC), duration of flowering, start of senescence, and maturity were also recorded. In each crop growth stages, green leaves were separated and leaf area of each plant measured by leaf area meter to obtain leaf area index (LAI), which was converted to crop canopy cover (CC). Dry biomass of above ground plant at each crop growth stages was obtained by weighing it after

Table 2. Physical and chemical properties of the soil of experimental field

Determination		Soil Depth (Cm)	
		0-30	30-60
Physical	Sand (%)	43	43
	Silt (%)	21	21
	Clay (%)	36	36
	FC (w/w)	39	39
	PWP(w/w)	23	23
	Ks (Cm day^{-1})	27.4	26.2
	Saturation, (%)	54	66
Chemical	EC (ds m^{-1})	0.176	0.175
	PH	6.0	6.27
	Organic carbon (%)	1.7	0.8
	Total N (%)	0.149	0.084
	P (ppm)	7.4	3.4
	K (ppm)	138	99

Ks: Saturated Hydraulic Conductivity, FC: Field Capacity, PWP: Permanent Wilting Point, EC: Electrical Conductivity

keeping in the oven for 48 h at 65° C. Besides this, the canopy decline coefficient, crop coefficient for transpiration at full canopy cover, soil water depletion thresholds for inhibition of leaf growth and stomatal conductance, acceleration of canopy senescence were used from Hsiao et al. (2009). These parameters were presumed to be applicable to a wide range of conditions and not specific for a given crop cultivar (Heng et al. 2009). Relationship between LAI and CC used for maize crop is presented in Eq. (3) (Hsiao et al. 2009; Heng et al. 2009). The crop parameters used as input to AquaCrop are presented in Table 3.

$$CC = 1.005[1-\exp(-0.6\times LAI)]^2 \quad (2)$$

The upper and lower thresholds and the shape of the response curve are the parameters for each type of stress that define the sensitivity and severity of a depleted soil profile. The upper threshold determines when the stress begins, while the lower threshold is the point at which the physiological process completely ceases. The shape factor used in AquaCrop model describes the amplitude of the stresses which affect the crop yield. A shape factor of zero indicated highest sensitivity of crop to water stress and more than zero is an indicative of less sensitiveness to water stress. The water stress is divided to expansion stress, stomatal closure stress and senescence stress coefficients. These coefficients were calibrated using the experimental data to obtain a better match between the AquaCrop simulated and observed data.

Calibration of AquaCrop model

Calibration of the AquaCrop model was accomplished by using the observed values from the field experiment during 2012 as model input and then simulating the model to predict the output *viz.* the yield and biomass. Subsequently, the predicted output values were compared with the observed yield and biomass of the experimental plot. The difference between the model predicted and experimental data were minimized by using trial and error approach in which one specific input variable was chosen as the reference variable at a time and adjusting only those parameters that were known to influence the reference variable the most. The procedure is repeated to arrive at the closest match between the model simulated and observed value of the experiment for each treatment combination.

The calibrated crop parameters used in AquaCrop model are presented in Table 3.

Model evaluation criterion

AquaCrop model simulation results of maize yield and biomass were compared with the observed values form the experiment during both calibration and validation processes. The goodness of fit between the simulated and observed values was corroborated by using the prediction error

Table 3. Calibration of crop parameters used in AquaCrop model

Description	Value	Unit
Base temperature	8.0	°C
Cut-off temperature	30.0	°C
Canopy growth coefficient(CGC)	19.9	% day^{-1}
Canopy decline coefficient (CDC) at senescence	1.06	% day^{-1}
Leaf growth threshold (P_{upper})	0.17	% of TAW [fraction of total available water (TAW)],
Leaf growth threshold (P_{lower})	0.75	% of TAW
Leaf growth stress coefficient curve shape	2.8	Unit less (Moderately convex curve)
Stomatal conductance threshold (P_{upper})	0.5	Unit less
Stomatal stress coefficient curve shape	1.7	Unit less (High convex curve)
Senescence stress coefficient curve shape	1.5	Unit less (Moderately convex curve)
Senescence stress coefficient (P_{upper})	0.21	Unit less (Initiation of canopy senescence)
Coefficient , inhibition of leaf growth on HI	6.0	Unit less (HI increased by inhibition of leaf growth at anthesis)
Coefficient, inhabitation of stomata on HI	2.7	Unit less (HI increased by inhibition of stomata at anthesis)
Maximum basal crop coefficient (K_{cb})	1.15	Unit less
Length of the flowering stage	15	days

statistics. The prediction error (P_e), coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE) and normalized root mean square error ($RMSE_n$) were used as the error statistics to evaluate both the calibration and validation results of the model. The R^2 was used to access the predictive power of the model while the Pe, $RMSE_n$ and RMSE indicated the error in model prediction. In this study, the model output in terms of prediction for grain yield and above ground biomass during harvest was considered for evaluation of the model. The following statistical indicators were used to compare the measured and simulated values.

$$P_e = \frac{(O_i - S_i)}{O_i} \times 100 \qquad (3)$$

Where: S_i and O_i are predicted (simulated) and actual (observed) data, $\bar{o}_i$ is mean value of O_i and N is the number of observations.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(O_i - S_i)^2} \qquad (4)$$

$$RMSE_n = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(O_i - S_i)^2} \times \frac{100}{\bar{O}_i} \qquad (5)$$

$$MAE = \sqrt{\sum_{i=1}^{n}(S_i - O_i)/n} \qquad (6)$$

The prediction is considered excellent with the $RMSE_n$ <10 %, good if 10–20 %, fair if 20–30 %, poor if >30 % (Jamieson et al. 1991).

RESULTS AND DISCUSSION

Grain yield, above ground biomass, under non- limiting fertilized (N_4), moderate fertilized (N_3), poor fertilized (N_3) and non-fertilized (N_4) conditions for 2012 experiments are shown in Tables 4 and 5. It was observed from the Table 5 that during two years of experiment, the lowest grain yields and biomass was observed to be 3054 and 6214 kg ha^{-1} in irrigation interval at 18 days, (F_3) and non-fertilized (N_1) treatment and the highest was 9542 and 19378 kg ha^{-1} under irrigation interval 6 days (F_1) and recommended dose of nitrogen (N_1), respectively. These results were the average of three replications pertaining to the experiments conducted during 2012. This could possibly be due to the fact that the senescence of the canopy accelerates under severe water stress, and the underground root system may be restricted and prevented from extracting more deeply stored soil water, thereby limiting its water uptake. Several authors (Heng et al. 2009; Zeleke et al. 2011; Abedinpour et al. 2014) reported more deviations under severe water stress or rainfed treatments, as compared to well-watered treatments for maize, teff and canola crops simulated by AquaCrop. AquaCrop model was calibrated using experiment data of 2012 to predict grain yield and biomass under different water and fertilizer application levels in the experiment. Model simulated and measured above ground biomass and grain yield under all nitrogen levels, for 6, 12 and 18 days irrigation intervals, (Figs. 1, 2and 3). It was observed from these figures that the model predictions for above ground biomass were close to the observed values of all treatment combinations, (i.e. $0.87 \le R^2 \le 0.97$). Furthermore, the model predictions for grain yield were close to the observed values of all treatment combinations, (i.e. $0.82 \le R^2 \le 0.95$). It was observed that, the maximum and minimum error in grain yield prediction was in F_3(18 days interval irrigation) and F_1 (6 days

Table 4. Calibration results of biomass, grain yield of maize under different irrigation intervals and N fertilizer

Treatments	Yield (k ha^{-1})		P_e	Biomass (t ha^{-1})		P_e
	Obs.	Sim.	(±%)	Obs.	Sim.	(±%)
Non-limiting fertilized dose (N_4):240 kg ha^{-1}						
F_1: 6 days	9.494	9.245	2.6	19.378	20.644	-6.5
F_2: 12 days	7.903	8.647	-9.4	19.288	20.012	-3.8
F_3: 18 days	4.157	3.883	6.6	10.053	9.503	5.5
Moderate-limiting fertilizer level (N_3):180kg ha^{-1}						
F_1: 6 days	7.187	7.214	-0.4	17.116	17.176	-0.4
F_2: 12 days	7.049	7.188	-2.0	16.542	17.113	-3.5
F_3: 18 days	4.344	3.937	9.4	9.100	8.847	2.8
poor- fertilizer level (N_2): 120kg ha^{-1}						
F_1: 6 days	6.445	5.742	10.9	14.514	13.117	9.6
F_2: 12 days	5.454	5.247	3.8	13.435	13.110	2.4
F_3: 18 days	3.988	3.804	4.6	9.101	8.230	9.6
Non- fertilizer level (N_1): 0						
F_1: 6 days	4.214	4.147	1.6	13.195	11.208	15.1
F_2: 12 days	4.684	4.147	11.5	11.610	11.208	3.5
F_3: 18 days	3.054	3.426	-12.2	6.214	7.768	-25.0

Obs. Observed; Sim. Simulated; P_e : Prediction error

Table 5. Prediction error statistics of the calibrated AquaCrop model

Model output parameters	Mean		RMSE	RMSE$_n$ (%)	Pe	MAE	R^2
	Measured	Simulated					
Grain yield (t ha^{-1})	5.430	5.511	800	15	-1.5	103	0.87
Biomass (t ha^{-1})	13.379	13.329	1380	10	0.37	269	0.92

interval irrigation) treatments amounting to 0.4% and 12.2%, respectively (Table 4). The prediction error in biomass for F$_3$ and F$_1$ treatments were -0.4% and -25%, respectively (Table 4). The prediction error statistics of the calibrated model is presented in Table 5. It was observed from Table 5 that the model was calibrated for simulation of yield and biomass for all treatment levels with the prediction error statistics $0.37<Pe<-1.5$, $0.8<RMSE<1.38$ t ha^{-1}. Also, RMSE$_n$ were 15 and 10 for grain yield and biomass, respectively. AquaCrop model predictions for grain yield and biomass were in line with the observed data corroborated R^2 values approaching one.

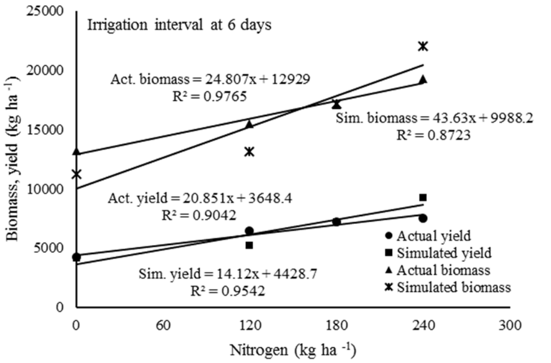

Fig.1 Model calibration results for grain yield and biomass for 6 days interval irrigation under all nitrogen levels

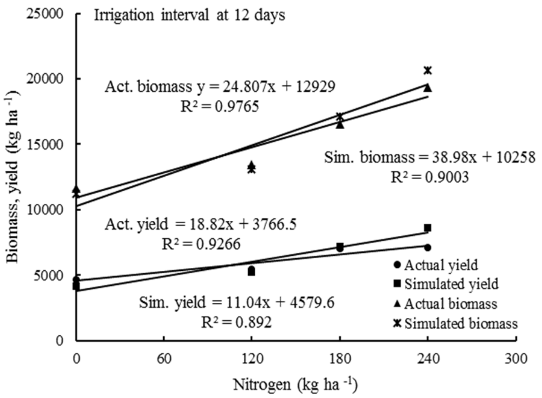

Fig.2 Model calibration results for grain yield and biomass for 12 days interval irrigation under all nitrogen levels

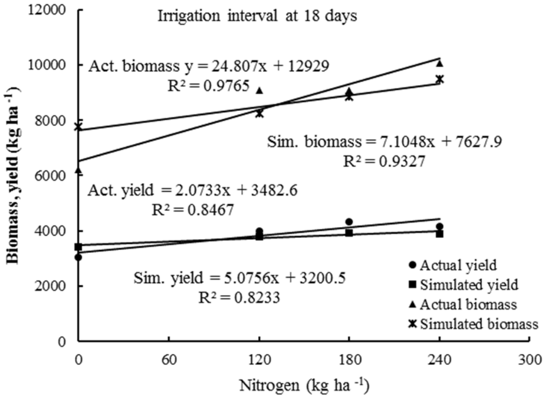

Fig.3 Model calibration results for grain yield and biomass for 18 days interval irrigation under all nitrogen levels

CONCLUSION

It was observed that, the AquaCrop model calibrated the grain yield and biomass with the prediction error statistics of $0.37<Pe<1.5$, $0.8<RMSE<1.38$ t ha^{-1} for irrigation and nitrogen treatment levels. It was obserevd that the Aquacrop model was more accurate in predicitng the maize yield under 6 and 12 days irrigation interval as compared to 18 days irrigation interval. AquaCrop model required lesser number of inputs data in simulating the maize growth and yield under different water and fertilizer availability scenarios, as compared to other crop models. Also, model cannot provide satisfactory results under severe water stress conditions. Nonetheless, from the results of field experiment and modeling, it can be concluded that the water driven FAO AquaCrop model could be used to predict the maize yield with acceptable accuracy under variable irrigation and field management situations.

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