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Improving Crop Production by Field Management Strategies using Water Driven Crop Model

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Abstract

Irrigation water is a major limiting factor in agricultural production. Crop growth simulation models of varying complexity have been developed for predicting the effects of water, soil, and nutrients on the grain and biomass yields and water productivity of different crops. Hence, a field experiment was conducted at Gorgan city in Iran to calibrate a water productivity model, Aquacrop, for soybean, in 2011. Irrigation applications comprised irrigation at (W_1): 60 %, (W_2): 70 %, (W_3): 80 %, and (W_4): 100 % of field capacity (FC). The results showed that the simulated water productivity (WP), biomass yield (BY), and grain yield (GY) using the Aquacrop model were consistent with the measured GY, BY, and WP, with corresponding coefficients of determination (R^2) of 0.96, 0.90, and 0.87, respectively. The root mean square error (RMSE) and model efficiency (E) for GY and BY ranged from 0.87 to 0.96, 0.1 to 1.2, and 0.87 to 0.96, respectively. Therefore, the Aquacrop model is a useful decision making tool for use in efforts to optimize soybean irrigation management.

Keywords: Aquacrop model, calibration, Gorgan, soybean, deficit irrigation

Introduction

Increasing grain production to feed the fast growing world population, particularly in developing countries, relies on 2 options: either increase the amount of arable land, or improve the productivity of the existing cultivated land. These countries, particularly in South-East and West Asian countries, are considered very vulnerable to climate change, where farmers could suffer unstable food supply due to decline in yield, constrained income due to increased input for sustaining crop productivity, and from other loss due to extreme event damage [1-6]. Many crop growth models, based on physiological processes, have been developed and applied in water management projects, with varying degrees of success. Many of these models, however, have not yet been tested under deficit irrigation in the summer seasons. For example, the CROPWAT model cannot be used for crop simulation, because it has the problem of simulating evapotranspiration and, therefore, the crop yield reduction estimates resulting from this model should be taken with caution [7]. The water-driven crop growth models assume a linear relation between biomass growth rate and transpiration through a water productivity (WP) parameter [8]. This approach avoids the subdivision into different hierarchical levels, which results in a less complex structure and reduces the number of input parameters [9,10]. The water-driven growth concept is used in the CropSyst and AquaCrop models. 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 [9].

Crop models, *viz.* CERES-Maize [11], the WOFOST model, CropSyst [12] and the Hybrid-Maize model [13], have been used for the prediction of maize crop yield. Most of these models, however, are quite sophisticated, require advanced modeling skills for their calibration and subsequent operation, and require a large number of model input parameters. Some models are cultivar-specific and are not easily amenable for general use. In this context, the recently developed Food and Agriculture Organization (FAO) AquaCrop model [12] 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 the experimental data of 6 cropping seasons in the University of California Davis, USA [14]. They observed that AquaCrop was able to simulate the Canopy cover (CC), biomass development, and grain yield of 4 maize cultivars over 6 different cropping seasons that differed in plant density, planting date, and evaporative demands. The AquaCrop model, developed by FAO, was calibrated and validated for *kharif* maize crop (BIO-9681) under varying irrigation and nitrogen regimes. The experiment was conducted at the research farm of the Water Technology Centre, IARI, New Delhi, during *kharif* 2009 and 2010. Calibration was done using the data of 2009 and validated with the data of 2010. Irrigation applications comprised rainfed i.e., no irrigation (W_1), irrigation at 50 % of field capacity (FC) (W_2), at 75 % FC (W_3), and full irrigation (W_4). Nitrogen application levels were no nitrogen (N_1), 75 kg ha^{-1} (N_2), and 150 kg ha^{-1} (N_3). Model efficiency (E), coefficient of determination (R^2), Root Mean Square error (RMSE) and Mean Absolute Error (MAE) 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 statistics being $0.95 < E < 0.99$, $0.29 < RMSE < 0.42$, $0.9 < R^2 < 0.91$ and $0.17 < MAE < 0.51$ t ha^{-1}. Upon validation, E was between 0.95 and 0.98, MAE was between 0.11 and 1.08, and RMSE was between 0.1 and 0.75 for grain and biomass yields, respectively. The prediction error in the simulation of grain yield and biomass under all irrigation and nitrogen levels ranged from a minimum of 0.47 to 5.91 %, and maximum of 4.36 to 11.05 %, respectively. Overall, the FAO AquaCrop model predicted maize yield with acceptable accuracy under variable irrigation and nitrogen levels [15]. Apart from this, another important issue that should be considered for irrigation scheduling is to assess cropping intensity, which can help managers and experts with accurate scheduling to dedicate water resources and to design a suitable cropping pattern for farmers. For this purpose, a study was done to investigate the variations of cropping intensity in Asia Oceania, Europe, and the Americas from 1962 to 2011 using information from the FAO. The results indicated that the attention to exclusively commercial goals should be reduced, trial and error policies should be avoided, and expert comments be applied to irrigation systems in order to allow any crop to achieve sustainable agriculture in future [3,5,6]. Therefore, in this research, the water productivity model AquaCrop was used as a tool to test different field management strategies for improving productivity of soybean under the local environmental conditions at the Gorgan plain, Iran. The model estimates yield by relating crop transpiration with biomass and yield production, and allows users to simulate yield under various conditions.

Materials and methods

Experimental site

A field experiment was conducted at the Asrieh field of Ozineh district in Gorgan city, Iran. The experimental field was located at 36° 51' N Latitude and 54° 29' E Longitude, at an elevation of 86 m above mean sea level (**Figure 1**).

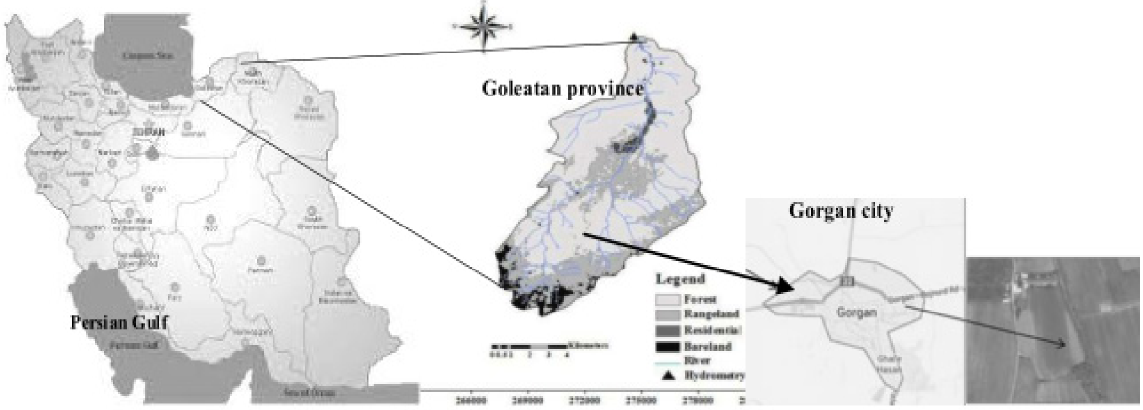

Figure 1 Location of field experiment site at Asrieh field in Gorgan city, Iran.

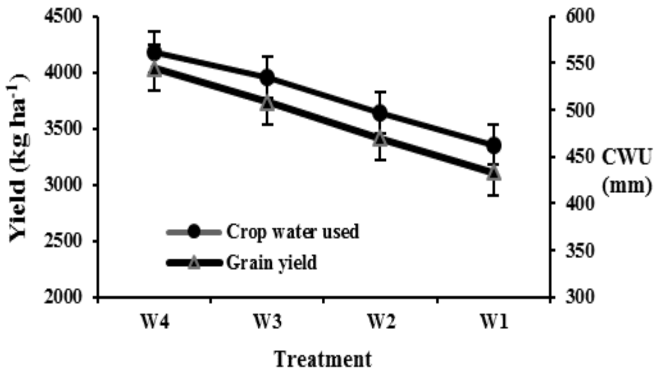

Figure 2 Grain yield and Crop water used (CWU) under different irrigation water treatments.

Potential evapotranspiration

Evapotranspiration (ETo) is the combination of soil evaporation and crop transpiration. Owing to the difficulty of obtaining accurate field measurements using lysimeters, ETo is commonly computed from weather data. A large number of empirical or semi-empirical equations have been developed for assessing reference evapotranspiration from meteorological data. The use of reference evapotranspiration leads to increasing uncertainty comparing actual evapotranspiration. There are other models that can estimate evapotranspiration reference that have had successful results. Also, numbers of empirical equations are useful for selecting the best model for when researchers must apply temperature-based models on the basis of available data [16-22]. Numerous researchers have analyzed the performance of the various calculation methods for different locations (Valipour). Valipour provided a comprehensive list for various ETo methods appropriate for regions with limited weather data availability. Also, an investigation of Valiantzas' evapotranspiration equation was done in Iran. The goal of this study was a comparison of the 5 forms of Valiantzas' evapotranspiration methods and the Priestley-Taylor and Turc models to detect the best one under different weather conditions. For this purpose, weather parameters were collected from 181 synoptic stations in 31 provinces of the country. Then, ETo was compared with the FAO Penman-Monteith method. The results indicated that they are suitable for provinces of Iran, with a coefficient of determination (R^2) greater than 0.99 [16-22]. As a result, the FAO Penman-Monteith method is now recommended as the standard method for the definition and computation of the reference evapotranspiration ETo. Meteorological data was collected through a weathering station, and this data was utilized for reference ETo calculation using a ETo calculator which is considered in the AquaCrop model. The averages of the meteorological data of the cropping period are shown in **Table 1**.

Table 1 The average of meteorological data in 2011.

Month	Temperature (°C)		Wind speed (m/sec)	Rainfall (mm)	RH (%)
	Min	Max			
June	26.9	33.4	1.51	2.30	65.9
July	25.05	34.9	1.42	1.42	61.3
August	24.6	33.7	1.72	14.4	73.6
September	24.0	31.8	1.11	21.8	78.8
December	23.7	29.6	1.30	87	79.8

Field management

The experiment was laid with a split plot design having 4 irrigation levels, *viz.* irrigations at (100, 90, 80, and 70) per cent of field capacity, with 3 replications. There were 5 furrows in each plot of 2.8×3 m^2 size, and 3 replications were separated by 2 m. Physical and chemical soil properties of the field experiment are presented in **Tables 2** and **3**, respectively. The soybean seed (*Williams*) was sown with a population density of 40 plants per m^2 on 15^{th} May, 2011. 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);

$$SMD = (\theta_{FC} - \theta_i) \times B_d \times D_{rz} \times f \qquad (1)$$

where SMD: Soil moisture deficit (mm),
θ_{FC}: Soil water content at field capacity,
θ_i: Soil water content at before irrigation crops (weight percent),
D_{rz}: Depth of root development (mm),
B_d: Bulk density of the particular soil layer (g cm^{-3}),
f: Coefficient of each treatment.

Table 2 Soil physical properties of the experiment field.

Soil depth (cm)	Soil texture	FC (%) (v/v)	PWP (%) (v/v)	B_d (g/cm^3)
0 - 10	Si. C. loam	44.02	23.43	1.25
10 - 20	Si. C. loam	41.00	21.67	1.27
20 - 30	Clay loam	38.50	18.82	1.32
30 - 40	Clay loam	37.50	18.29	1.33
40 - 60	Clay loam	36.50	17.21	1.33
60 - 80	Clay loam	35.00	16.03	1.34

FC: field capacity, PWP: permanent wilting point, B_d: bulk density, AW: available water

Table 3 Some chemical properties of the experiment soil.

Soil depth (cm)	PH	EC (dS/m)	TDS (ppm)	Na^+ (meq /100g soil)	Ca^{2+} (meq /100g soil)	Mg^{2+} (meq /100g soil)
0 - 30	7.8	0.62	427.2	1.98	0.79	0.04

Moreover, the dates of irrigations in this study were determined when soil moisture in the root zone approached 50 % of the total available water (TAW) and was considered as the manageable allowable deficit (MAD) at 50 %. Further, the measured quantity of irrigation was applied for a depth from the existing moisture level up to the field capacity using Eq. (1) to ensure that there was no loss of water. Thus, the depth of irrigation water was estimated for the full irrigation treatment (W_4) for a given date based on the existing soil moisture. Subsequently, the deficit irrigation treatments at 70 % (W_1), 80 % (W_2), 90 % (W_3), and 100 % (W_4) levels were estimated by multiplying the coefficient "f" of 0.7, 0.8, 0.9, and 1 with the depth estimated for full irrigation treatment (W_4). Moreover, all of the irrigation treatments were done on the same day during the crop growth period. Evapotranspiration (ET, mm) for each treatment was calculated according to the water-balance approach [10];

$$ET = I + P - D_p - R_f + \Delta sw \tag{2}$$

where I: irrigation water applied during the growth period (mm),
P: effective rainfall during the growth period plus capillary rise (mm),
D_p: amount of drainage water (mm),
R_f: amount of runoff (mm), and
Δ_{sw}: change in the soil moisture content (mm) estimated by gravimetric sampling.

Since there was no runoff during irrigations and the water table was at 4 m depth, capillary flow to the root zone and runoff were assumed to be negligible in the calculation of ET. Based on a number of soil-water content measurements, drainage below 90 cm was considered to be negligible. Thus, the above equation was reduced to;

$$ET = I + P + \Delta sw \tag{3}$$

The conveyance loss was avoided by use of gated PVC pipes for the supply of water from the source to the experimental plots. The soybean seeds were sown at a depth of 3 cm. A recommended dose of P_2O_5 (100 kg/ha), k_2O (80 kg/ha) were applied to the soil before sowing. The N fertilizer was applied with 3 split doses, with one-third given as basal, one-third at 20 days after sowing (DAS), and the remaining at 50 DAS of the crop. Hoeing was done to keep the crop free from weeds. In order to measure yield and yield components, plants from the 3 middle rows of each plot were harvested, representing at the physiological maturity stage of the crop. The data collected was analyzed statistically by using Fisher's analysis of variance techniques, and differences among treatment means were compared using the least significant difference test at a 5 % probability level.

AquaCrop model

Input data and calibration of the AquaCrop model

AquaCrop uses six input files for simulation: climate file, crop file, soil file, management file, irrigation file, and initial soil water conditions; all these are user specific. The climate file consists of 3 sub-files: (i) minimum and maximum air temperature, (ii) ETo, and (iii) rainfall, all with daily values as described [4]; the crop file contains both conservative parameters (that do not change with location) and user-specific parameters (non-conservative) [12]. Pointing out those minor changes in initial soil water content (e.g., from 8.5 to 10.5 vol %) resulted in major changes in the model output (400 kg/ha additional biomass and 250 kg/ha additional yield). The parameters used for the AquaCrop model were measured or estimated using experimental data; some were based on field experience, and some used the default values given in the model, regardless of the year (**Table 6**). Before using AquaCrop for developing the response to water stress and fertility stress in soybean, the model had to be calibrated and validated for the relevant conditions. Experimental field data collected were used to calibrate and evaluate the model. The calibration was done through an iterative process, using the measured crop growth variables, observed phonological stages, parameters estimated from available data, and derived growing coefficients. The final phase of calibration consisted of the refinement of other parameters, so that the simulated value (GY) fit well with the observed data.

The model simulated grain yield (GY), biomass yield (BY), and water productivity (WP) of soybean. The canopy expansion rates were automatically estimated by the model after entering phonological dates, such as dates to emergence, maximum canopy cover, senescence, and maturity. The main calibration parameters for CC included the CGC, the canopy decline coefficient (CDC), water stress (p upper, p lower, and shape factor) affecting leaf expansion, and early senescence. The measured canopy cover was reproduced by adjusting the stress coefficients. **Table 4** presents some of the results of the parameterization of AquaCrop for soybean. Based on a figure that was developed for the relationship between biomass and cumulative normalized transpiration, the value of 14 g/m^2 was found for normalized water productivity, as shown in **Table 4**, and the value of WP* started to reduce at the time of flowering.

Table 4 Calibration values for selected parameters of the crop file of AquaCrop model.

Description	Value	Unit
Base temperature	8.0	°C
Cut-off temperature	35.0	°C
Canopy growth coefficient(CGC)	10.9	% /day
Canopy decline coefficient (CDC) at senescence	1.06	% /day
Leaf growth threshold (P_{upper})	0.14	% of TAW [fraction of total available water (TAW)]
Leaf growth threshold (P_{lower})	0.62	% of TAW
Leaf growth stress coefficient curve shape	3.4	Unit less (Moderately convex curve)
Expansion stress coefficient (P_{upper})	0.1	% of TAW
Expansion stress coefficient (P_{Lower})	0.3	% of TAW
Expansion stress coefficient curve shape	2.3	% of TAW
Stomatal conductance threshold (P_{upper})	0.5	Unit less
Stomatal stress coefficient curve shape	1.8	Unit less (High convex curve)
Senescence stress coefficient curve shape	1.3	Unit less (Moderately convex curve)
Senescence stress coefficient (P_{upper})	0.6	Unit less (Initiation of canopy senescence)
Normalized water productivity	14	g/m^2
Maximum basal crop coefficient (K_{cb})	1.15	Unit less
Time from sowing to emergence	6	days
Time from sowing to start flowering	54	days
Time from sowing to start senescence	88	days
Time from sowing to maturity	104	days

Model evaluation

The AquaCrop model simulation results of soybean yield, biomass yield and WP were compared with the observed values from the experiment during the calibration processes. The goodness of fit between the simulated and observed values was corroborated by using the prediction error statistics. The prediction error (P_e), coefficient of determination (R^2), mean absolute error (MAE), root mean square error (RMSE), and model efficiency (E) were used as the error statistics to evaluate the calibration results of the model. The R^2 and E were used to assess the predictive power of the model, while the Pe, MAE, and RMSE indicated the error in model prediction. In this study, the model output, in terms of prediction for canopy cover, grain yield, and above ground biomass during harvest, were considered for evaluation of the model. The following statistical indicators were used to compare the measured and simulated values. Model performance was evaluated using the following statistical parameters, such as model efficiency (E) [23], given by;

$$P_e = \frac{(S_i - O_i)}{O_i} \times 100 \tag{5}$$

$$E = 1 - \frac{\sum_{i=1}^{N} (O_i - S_i)^2}{\sum_{i=1}^{N} (O_i - \overline{O})^2} \tag{6}$$

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

$$RMSE = \sqrt{1/(N) \sum_{i=1}^{N} (O_i - S_i)^2} \tag{7}$$

$$MAE = \sqrt{\sum_{i}^{N} (S_i - O_i) / N} \tag{8}$$

Model efficiency (E) and R^2 approaching one and Pe, MAE, and RMSE close to zero were indicators of better model performance.

Results and discussion

Effects of different irrigation water amounts on yield

The data presented in **Table 5** shows the effect of different irrigation water amounts on grain yield. The statistical analysis of data indicated that different irrigation water treatments had no significant effect on the yield. Maximum yield was obtained in the full irrigation treatment at (4.18 t/ha), while W_1 treatment (70 % FC) recorded the lowest value of (3.35 t/ha).

Water productivity (WP)

The term "water use efficiency" has been widely used in irrigation crop production to describe the efficiency of irrigation with respect to crop yield production from the standpoint of water conservation and production cost. Water use efficiency, as used in this discussion, is defined as kg of grain yield per depth of water consumed by crop or applied. Values of crop and yield water use efficiency are presented in **Table 5**. The results show that the irrigation at 90 % of field capacity treatment (W_3) recorded the highest value of crop water use efficiency (7.79 kg/ha/mm), while the lowest value was obtained in the irrigation at 100 % FC treatment (W_4), at (7.67 kg/ha/mm).

Yield calibration

Calibration of yield simulation was done by assessing the goodness of fit of the simulated against the observed yield. The average grain yield was observed to be 3.78 t/ha, while the simulated yield was 3.51 t/ha. This showed that the model underestimated the yield and, hence, the need to adjust the harvest index from 0.45 to 0.55 %. The regression of simulated against observed grain yield was also considered to assess the correctness of the simulations during the calibration of grain yield (**Table 6**). The value of R^2 = 0.96 showed a strong relationship between observed GY and simulated GY, meaning that the model gave very good predictions (**Table 7**).

Table 5 Effect of different depths of irrigation on yield and WUE of soybean.

Treatments	Grain yield (Kg/ha)	Biomass (Kg/ha)	Depth of water applied (mm)	Crop water used (mm)	WP (kg/ ha/ mm)	HI (%)
100 % (FC)	4180	6742	375	545	7.67	0.62
90 % of FC	3955	6592	338	508	7.79	0.6
80 % of FC	3640	6275	300	470	7.74	0.58
70 % of FC	3355	6213	263	433	7.75	0.54

Table 6 Calibration results of biomass and grain yield of soybean under different irrigation water and fertilizer regimes.

Treatments	Yield (t/ha)		P_e (±%)	Biomass (t/ha)		P_e (±%)	WP (kg/mm/ha)		P_e (±%)
	Obs.	Sim.		Obs.	Sim.		Obs.	Sim.	
W_1 (70 % FC)	3.35	3.11	7.16	6.07	5.47	9.9	7.75	8.30	6.3
W_2 (80 % FC)	3.64	3.38	7.14	6.28	5.84	7.0	7.74	8.32	6.2
W_3 (90 % FC)	3.95	3.65	7.6	6.59	6.17	6.37	7.79	8.02	6.1
W_4 (100 % FC)	4.18	3.90	6.70	6.74	6.35	5.8	7.67	8.11	5.6

Table 7 Prediction error statistics of the calibrated AquaCrop model.

Model output parameters	Mean		RMSE	E	MAE	R^2
	Measured	Simulated				
Grain yield, t/ha	3.78	3.51	0.1	0.98	0.11	0.96
Biomass, t/ha	6.42	5.96	0.75	0.95	1.08	0.90
WP, kg/ha. mm	7.74	8.21	1.20	0.74	0.79	0.87

Biomass calibration

When running AquaCrop after calibration of the canopy, the simulated above ground biomass matched the observed. The model estimates of the biomass on the following days, 30, 45, 60, and 115, correctly simulated the above ground biomass. This indicated that the model could simulate biomass under the conservative normalized water productivity (WP_b*) reference of 14.0 g/m^2, so there is need to change it. The regression of simulated against observed final above ground biomass was also considered to assess the correctness of the simulations during the calibration of biomass (**Table 6**). The value of R^2 = 0.96 showed a strong relationship between observed biomass and simulated biomass, meaning that the model gave very good predictions (**Table 7**).

Conclusions

This results demonstrated that the AquaCrop model adequately simulated the GY, BY, and WP of soybean under different irrigation strategies. The simulated GY, BY, and WP agreed well with the measured values. The R^2, RMSE, and E ranged from 0.87 to 0.96, 0.1 to 1.2, and 0.87 to 0.96, respectively. The results demonstrated that frequent irrigation obviously improved BY, GY, biomass WP, and grain WP for soybean in 2011. These results suggest that the AquaCrop model could be used to predict the BY and GY of soybean with a high degree of reliability under various irrigation strategies at the Gorgan plain.

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