PHILIPP AGRIC SCIENTIST
Vol. 107 No. 1, 29-38
March 2024

ISSN 0031-7454

Evaluation of the AquaCrop Model for Simulating Cotton Yield Under a Semi-Arid Environment and Different Field Management Practices

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Received: May 02, 2022 / Revised: March 27, 2023 / Accepted: March 31, 2023

Cotton plays an important role in increasing productivity in the agricultural sector and related industries in the province of Golestan, Iran. However, the cultivation areas decreased considerably in the last couple of decades due to the high costs of production, water scarcity, and climate change. To encourage sustainable increase in production, crop simulation models are parameterized for each region using observed field data. In this study, the AquaCrop model was calibrated and validated for cotton under different field management scenarios using data from a 3-yr field experiment, which was conducted at the research farm of the National Cotton Research Institute, Golestan, Iran. The field experiment comprised six irrigation treatments (W1: rainfed/no irrigation, W2: irrigation at 33% of water requirement [WR], W3: irrigation at 66% WR, W4: irrigation at 88% WR, W5: irrigation at 100% WR/full irrigation, and W6: irrigation at 125% WR/over-irrigation) and four rates based on the recommended dose of nitrogen (RDN) (N1: 0 or no N, N2: 33% RDN, N3: 66% RDN, and N4: 100% recommended RDN). The model was calibrated using data from the 1st experimental yr and validated with data from the 2nd and 3rd yr. Simulated and observed data of cotton yield and above ground biomass yield were compared, and the resulting prediction error statistics were $0.85 < E < 0.93$, $0.27 < RMSE < 0.58$ t ha^{-1}, and $8.08 < MAE < 14.6\%$. Moreover, validation results for yield and biomass amounting to $0.85 < E < 0.92$ and $0.27 < RMSE < 0.58$ t/ha were calculated for 2013 and 2014. Overall, the AquaCrop model estimated cotton yield and biomass with reasonable accuracy under varying field conditions.

Keywords: calibration, cotton, deficit irrigation, nitrogen, validation

INTRODUCTION

In many water-scarce regions and even otherwise, water is predominantly used for irrigation. Water used for agricultural production accounts for about 75% of all usages in developing countries, and the FAO has estimated a 14% net increase in the use of water to meet food demands by the year 2030 (UNESCO-WWAP 2006).

In the province of Golestan, Iran, cotton is one of the crops that play many important roles in increasing income in the agricultural sector and related industries. In the last couple of decades, the cotton cultivation area in Gorgan County, Golestan's cotton-producing region, has decreased considerably due to water scarcity, high production costs, and climate change (Kalbali et al. 2021). The focus has changed to the limiting factors in production systems in recent years, especially the availability of either water or land. Hence, deficit irrigation (DI) management has been widely considered as an efficient strategy for arid and semi-arid regions (Fereres and Soriano 2007). However, field experimental research is usually costly and time-consuming. Thus, instead of field experiments, crop simulation models have been explored to duplicate crop responses to environmental stressors and to test alternate field management practices.

Several studies have shown that among crop models that are widely used, the AquaCrop model (Raes et al.

2009; Steduto et al. 2009) has a suitable and acceptable capability to simulate the growth and yield of different plants under different levels of irrigation and nitrogen fertilization. The AquaCrop model has been parameterized and evaluated on corn by using field data from six cropping seasons in the University of California Davis, USA (Hsiao et al. 2009). They revealed that the model was able to simulate the crop canopy cover (CC), grain, and dry matter yield of four corn cultivars over six different cropping seasons that differed in sowing date, plant density, and irrigation demands. Todorovic et al. (2009) compared the performance of a water-driven AquaCrop model with CropSyst and the WOFOST (WOrld FOod STudies) models for sunflower using deficit irrigation management in Italy. They suggested that the simpler model AquaCrop be recommended due to its less input data requirement and high estimation accuracy pertaining to yield and water productivity. Abedinpour et al. (2012) simulated the grain and biomass yield of maize crop under different irrigation water and nitrogen treatments using the AquaCrop model in New Delhi, India. The result indicated that estimation error in a simulation of grain and biomass yield under all treatments ranged from lowest values of 0.47% – 5.91% and highest values of 4.4% – 11.05%, respectively. Preliminary parameterization for cotton was done using single location data sets. Data from different locations, having completely different climate and soil conditions, were required to try to do additional complete parameterization of this crop (Farahani et al. 2009). Hussein et al. (2011) reported that in cases of limited input data for cotton prediction growth, AquaCrop could be a promising model for estimating crop productivity under deficit irrigation conditions. A field experiment was conducted in the growing seasons of 2012 – 2016 for cotton with drip irrigation, covering full irrigation (FI) or 100% of crop water requirement (WR), two over-irrigation (115% and 145% of FI) and two deficit irrigation treatments (55% and 90% FI) in a saline environment in Southern Xinjiang, China. The results indicated that simulations of CC, soil moisture and dry matter fitted well with the field measurements with a coefficient of determination $R^2 > 0.77$ and $d > 0.92$.

An important attribute of the modelling approach is that it permits extension of the sector findings to conditions not tested within the field. Thus, it is helpful in providing sensible suggestions that may facilitate in irrigation management choices. Therefore, the objectives of this study were to evaluate the AquaCrop model's performance for cotton grown in a semi-arid environment under different irrigation and nitrogen fertilizer treatments.

MATERIALS AND METHODS

Experimental Site

The field experiment was conducted in the Hashem Abad Cotton Research Station of Gorgan in Iran (Fig. 1) in 2012, 2013, and 2014. The field experiment was located between 36° 51′ N latitude and 55° 36′ 15″ E longitude at an average elevation of 14 m asl.

Field Treatments and Agronomy Practices

The factorial experiment was laid out in a randomized complete block design (RCBD) in three replications with six levels of water regimes and four levels of nitrogen amounts. The water regimes comprised the following: W1: no irrigation (rainfed); W2: irrigation at 33% of WR; W3: irrigation at 66% WR; W4: irrigation at 88% WR or deficit irrigation; W5: irrigation at 100% WR or full irrigation; and W6: 125% WR or over-irrigation. The nitrogen fertilizer regimes which were based on the recommended dose of N (RDN) were: N1: zero or no N; N2: 33% RDN; N3: 66% RDN; and N4: 100% RDN.

The cotton variety of Golestan was sown at a depth of 3 – 5 cm on the 15^{th}, 16^{th}, and 18^{th} of May during 2012, 2013, and 2014, respectively. Irrigation water was applied for the 100% irrigation treatment (W5) after 50% of total available water (TAW) depleted. In other irrigation treatments, water was applied at the same time with that of W5, but the depth of water was reduced to 33%, 66%, and 88% of the full irrigation (100% irrigation treatment) for W2, W3, and W4, and depth of water was increased to 125% WR for W6. Except in N1, nitrogen was applied in three split doses with 1/3 given at planting day (0 d after planting [DAP]), 1/3 at 40 DAP, and the remaining at 60 DAP. The yield was measured at the late crop growth stage (maturity stage) by selecting the three middle rows of each plot. For all plots, 10 plants were dried at 65°C for 48 h to get aboveground dry biomass.

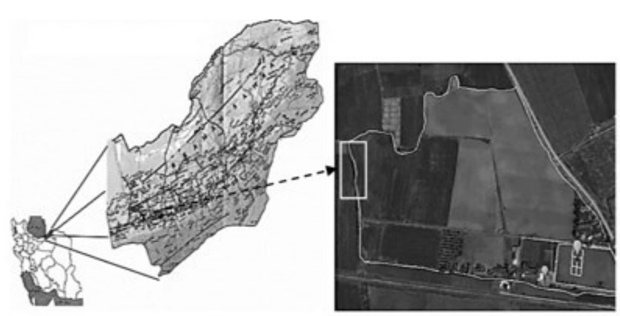

Fig. 1. Location of the cotton experimental field in Gorgan County, Golestan, Iran.

Data Collection and Calculations for AquaCrop Parameterization

The AquaCrop Model requires in situ data needed for parameterization, calibration, and validation. These data are generally related to the main components of the soil-plant-atmosphere continuum. The input data can be categorized into five components: climate, crop, soil, field, and irrigation management.

Climate Data

Daily climatic data were collected from the synoptic weather station situated 50 m from the experimental field. Data collected included the daily minimum and maximum air temperature (T_{min} and T_{max}), relative humidity (RH), precipitation (P), sunshine hours (SS), and wind speed at 2-m height (U2). Daily potential evapotranspiration (ET_O) was calculated using an ET_O calculator. The monthly weather parameters during the experiments in 2012, 2013, and 2014 are presented in Figs. 2 and 3, respectively.

Crop Parameters and Yield

Crop parameters in terms of growth periods, root length, canopy cover (CC), and biomass were determined. CC was measured using AccuPAR LP–80 (Fig. 4), a lightweight, portable, linear photosynthetically active radiation (PAR) senior (Decagon Devices, Inc.) at bi-weekly intervals. This instrument measures PAR in the 400 – 700 nm waveband. Measurements were done both at the top and below the cotton canopy at 12:00 AM in each plot. CC was then determined using Equation 1, where:

$$CC = 1 - (PAR_B/PAR_H) \quad (1)$$

PAR_B = amount of Photo-synthetically Active Radiation received at the bottom of the crop canopy.

PAR_H = amount of Photo-synthetically Active Radiation received at the top of the crop canopy

Also, dates of planting, emergence, flowering and its duration, time to reach maximum canopy cover, beginning of senescence, and maturity were monitored and recorded. In this study, water stress causes both stomatal and senescence stresses, which is recognized by different functions listed in Table 1. The lower (P_{lower}) and upper (P_{upper}) leaf growth thresholds and the leaf growth stress coefficient curve shape (P_{shape}) are the parameters for water stress that define the sensitivity and severity of depleted water from the soil root zone. The P_{upper} indicates the onset of the effects of water stress on plants, while the P_{lower} is the point at which the physiological process fully ceases. The P_{shape} in the AquaCrop model determines the amplitude of the water stress on the plant, which affects the yield. For example, a P_{shape} of 0 indicates the maximum sensitivity of plant to water stress and a result of more than 0 is an indication of less sensitivity to water stress.

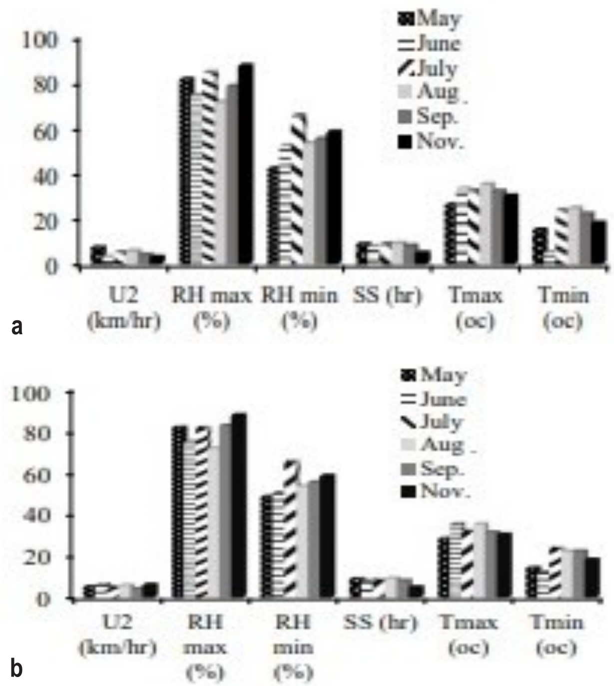

Fig. 2. Weather data during the crop-growing period in 2012 (a) and 2013 (b).

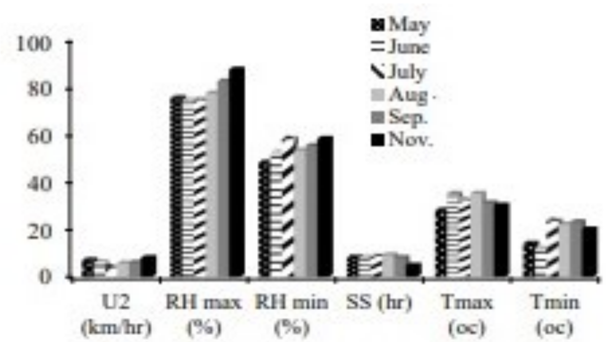

Fig. 3. Weather data during the crop-growing period in 2014.

Fig. 4. Measurement of PAR_H by using AccuPARLP-80 device.

Table 1. Input data of cotton crop used in AquaCrop model for calibration.

Description		Value	Unit
Base temperature		13.00	°C
Cut-off temperature		35.00	°C
Soil surface covered by an individual seedling at 90% emergence (CC_o)		6.50	(cm^2/plant)
Canopy growth coefficient (CGC)		0.0070	% day^{-1}
Canopy decline coefficient (CDC) at senescence		0.0024	% day^{-1}
Maximum canopy cover		95.00	(%)
Time from	sowing to emergence	7.00	day
	emergence to flowering	54.00	
	flowering to start of senescence	56.00	
	length of flowering	30.00	
Leaf growth threshold (P_{upper})		0.20	% of TAW [fraction of total available water (TAW)],
Leaf growth threshold (P_{lower})		0.70	% of TAW
Leaf growth stress coefficient curve shape		2.20	Unit less (Moderately convex curve)
Expansion stress coefficient (P_{upper})		0.00	% of TAW
Expansion stress coefficient (P_{Lower})		0.30	% of TAW
Expansion stress coefficient curve shape		1.30	% of TAW
Stomatal conductance threshold (P_{upper})		0.50	Unit less
Stomatal stress coefficient curve shape		1.01	Unit less (High convex curve)
Senescence stress coefficient curve shape		1.40	Unit less (Moderately convex curve)
Senescence stress coefficient (P_{upper})		0.19	Unit less (Initiation of canopy senescence)
Coefficient , inhibition of leaf growth on HI		6.00	Unit less (HI increased by inhibition of leaf growth at anthesis)
Coefficient, inhabitation of stomata on HI		2.50	Unit less (HI increased by inhibition of stomata at anthesis)
Maximum basal crop coefficient (K_{cb})		1.28	Unit less
Normalized Water Productivity (WP*)		13.70	g/m^2

Soil Parameters

Data relating to the soil of the experimental field needed as input parameters for AquaCrop were the quantity of soil horizons, soil texture, saturated hydraulic conductivity (K_s), soil water content at field capacity (FC), permanent wilting point (PWP), and saturation (θ_{sat}). The physical properties of the soil were determined after collection of soil samples from different depths of the field and subsequent air-drying and passing through a 2-mm sieve. The FC and PWP were obtained using the pressure plate apparatus at designated pressures of 0.3 and 15 bar, respectively. The K_s of the soil samples were measured using a constant head permeameter. The soil of the research field did not have any impenetrable layers which cause water logging, lack of aeration, and expansion and growth of the roots. The soil characteristics are presented in Table 2.

Irrigation and Field Management

In the field experiment, in situ soil moisture content (volume basis) was measured using time-domain reflectometry (TDR) before and after each irrigation event in all irrigation treatment plots. The soil moisture data was used to calculate the percentage depletion of total available water (TAW) in the treatment plots using Equation 2, where Θ_{fci} is soil water content at FC in each soil layer (m^3/m^3), Θ_i is soil water content before irrigation in each soil horizon (m^3/m^3), and Θ_{pwpi} is soil water content at PWP (m^3/m^3).

Table 2. Soil properties of cotton field experiment.

Soil depth	Soil texture	ρb (gr/cm³)	FC (%)	PWP (%)	K_s (m/day)	EC dS/m	pH
0 - 30	Si. C. L	1.52	28.30	14.20	2.30	1.10	7.70
30 - 60	Si. C. L	1.48	28.50	14.40		1.00	7.70
60 - 90	Si. C	1.45	28.80	14.50	2.10	1.00	7.50

ρb: bulk density, Si. C. L: silty clay loam, EC: electrical conductivity, Ks: saturated hydraulic conductivity.

$$\text{Depletion (\%)} = \frac{1}{n}\sum_{i=1}^{n}\frac{\theta_{fci}-\theta_i}{\theta_{fci}-\theta_{pwpi}} \quad (2)$$

Also, the net depth of irrigation—that is, the depth of water applied to refill the soil water content in the crop root zone to the FC—was calculated by using Equation 3, where p_b is the bulk density of the soil (g cm^{-3}), D_i is the depth of the ith soil layer (mm), and n is the number of soil layers.

$$d = \sum_{i=1}^{n}\frac{(\theta_{fci}-\theta_i)}{100}\times\rho_b\times D_i \quad (3)$$

In the full irrigation treatment (FI/W5), water was applied into the soil up to FC level when 50% of TAW in the root zone depleted. In the other treatments (33%, 66%, and 88% of FI), water was applied at the same time, but the irrigation water depths were reduced to 33%, 66%, and 88% of FI.

Model Calibration

The AquaCrop model simulates the growth of several crops as a function of CC. The model calculates the crop evapotranspiration (ETC) and separates it into crop transpiration (T_c, mm/d) and soil evaporation (E_S, mm/d) using the daily time step. In the newly updated crop model (AquaCrop Version 5.0), a reference evapotranspiration calculator (ET_O cal.) has been incorporated for the estimation of ET_O. The ET_O calculator estimates reference evapotranspiration from weather station data which includes Tmin and Tmax, U2, RH, and SS by means of the FAO Penman-Monteith equation. Thus, Tc was computed using Equation 4 below, where CC* is the CC adjusted by the micro-advective effects in percent, and K_{cTrx} is the highest transpiration coefficient (dimensionless).

$$T_C = CC^{*}K_{CTrx}ET_0 \quad (4)$$

Therefore, the T_c is calculated by the adjusted CC by the micro-advective effects (CC*, %), by the K_{cTrx} (Nunes et al. 2021). The K_{cTrx} is the highest transpiration coefficient (dimensionless) and is adjusted by the model taking into account the phenological stages and senescence of the culture. The D_R is a fraction of TAW in mm (Nunes et al. 2021). The D_R varies from 0 when soil water is in FC (i.e., 0% depletion, therefore K_S = 1) to 1, when the soil moisture is depleted (100% depletion, K_S = 0). When D_R exceeds RAW (RAW = pTAW), water tension begins to affect crop growth (Nunes et al. 2021). Hence, some irrigation management schedules could be designed with the assistance of the model. The model applies water before D_R reaches RAW when water stress is intended to be avoided.

Regarding the Es, it is also obtained from the CC* and ET_O through Equation 5:

$$E_S = K_R(1-CC^{*})K_{ex}ET_0 \quad (5)$$

Where K_{ex} (dimensionless) is the maximum evaporation coefficient of the soil and K_R (ranges from 0 to 1) is the coefficient of reduction of evaporation, when K_R < 1 means that there is the availability of water in the soil to respond to evaporative demand from the atmosphere. Therefore, in the model, the ET_C directly depends on the CC. Consequently, the model's ability to produce reasonable estimations of biomass and yield depends on the proper parameterization of the CC curve (Nunes et al. 2021).

The CC curve estimation occurs for the whole cycle, considering three crop growth stages (Raes et al. 2012). The first one starts in the initial growth stage (emergency); this stage is determined by the initial covering of the canopy in the soil (CC_o %) and ends when half of the maximum CC (CC_X %) is reached.

Sensitivity Analysis

The output parameters of the model were yield, biomass, water productivity (WP), and CC. The model input data were then categorized as low, moderate, and high sensitivity based on their effects on the output parameters (Table 3). The classes of high affectability were values of change surpassing 15%, moderate classes were values from 5% to 15%, and low classes reflected only 5% of variety of the model output.

Validation of the AquaCrop Model

After parameterizing the AquaCrop model, it was validated using the 2013 and 2014 data from the cotton research field. The parameterized model was applied to simulate the 2012 conditions. Simulated values of yields were compared with measured data and linear

Table 3. Sensitivity of model to varying input parameters for cotton.

High Sensitivity	Moderate Sensitivity	Low Sensitivity
	Crop inputs	
WP*	T_{CCx}	
HI	CC_X	Water extraction pattern
Root length	$T_{flowering}$	T_{rx}
	CC_o	
	Soil inputs	
PWP		Ks
FC		
	Climate inputs	
P	ETo, T_{air}	

T_{CCX}: Time to maximum canopy cover (CC_x); $T_{flowering}$: Time to flowering; T_{rx}: Time to maximum rooting depth; CC_o: initial canopy cover; CC_x: maximum canopy cover; HI: harvest index; P: precipitation.

regression analysis was done to find the correlations between simulated and measured data.

Model Evaluation

The simulation results of the model for yields and WP were compared with the measured data during the calibration and validation processes. The prediction error (P_e), R^2, average absolute difference (AAD), mean absolute error (MAE), root mean square error (RMSE), and model efficiency (E) were used to evaluate the model's performance.

$$P_e = \frac{(P_i - O_i)}{O_i} \times 100 \qquad (6)$$

$$E = 1 - \frac{\sum_{i=1}^{N}(O_i - S_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2} \qquad (7)$$

Where S_i and O_i are simulated and observed values, $\bar{O}_i$ is mean value of O_i and N is the number of measurements.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - S_i)^2} \qquad (8)$$

$$MAE = \sqrt{\sum_{i=1}^{N}(P_i - O_i)/N} \qquad (9)$$

$$AAD = \frac{|Pi - Oi|}{N} \qquad (10)$$

RESULTS AND DISCUSSION

Biomass and Yield Simulations

The results for the applied water depth for cotton are presented in Fig. 5. These values are the sum of the average of irrigation depths (three replicates) and effective rainfall. For model calibration, the simulated yields were compared to the observed data in the field.

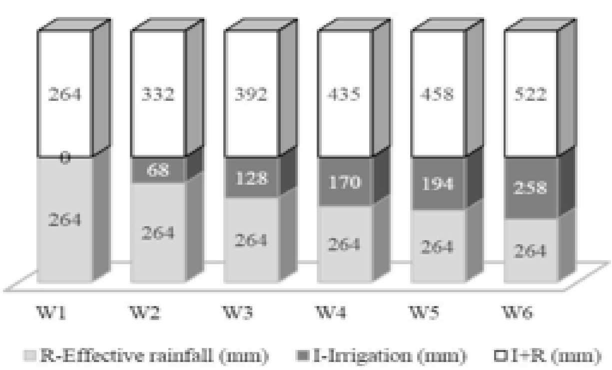

Fig. 5. Irrigation water depth, effective rainfall and total water received (Irrigation and effective rainfall) for all treatments.

Overall, along the 3-yr harvests, a good model performance for biomass simulations was observed, since it presented high efficiency (EF) in the simulation of yields, which resulted in values more than 0.97 (Figs. 6 and 7). Due to the low percentage of error prediction as well as the simulation results, it can be stated that the relevant model of the Golestan cultivar is well-calibrated. It was observed that the highest and lowest error in yield estimation was in W1N2 and W5N4 treatments with 17.5% and 2.12%, respectively. The P_e in biomass for W1N1 and W5N3 treatments were 16.5% and 4.7%, respectively (Table 4). In addition, the best model calibration results were achieved with estimation errors ranging from the lowest value of 3.01% for W5 to the highest value of 10.78% for W1 with all nitrogen treatments in 2012. Similarly, the maximum (10.5%) and the minimum P_e (3.7%) for biomass were observed for W2 and W3 in the season of 2012, respectively (Table 5). Estimation errors were acceptable (0.34% < RMSE < 2.61%, 8.08% < MAE < 14.6%, and 0.08 < AAD < 1.9) for these simulations due to the high EF of the model in the biomass simulation (Table 6). The model also showed good EF in the simulation of cotton yield in calibration for all treatments adopted. On the other hand, all treatments showed a low difference between the observed and simulated yield values, ranging from 2.12 to 17.5.

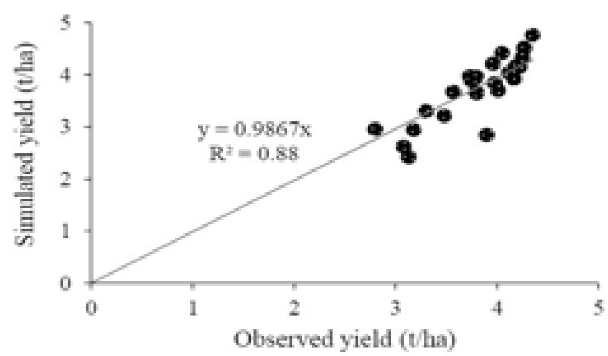

Fig. 6. Calibration results for cotton yield under all irrigation and nitrogen levels.

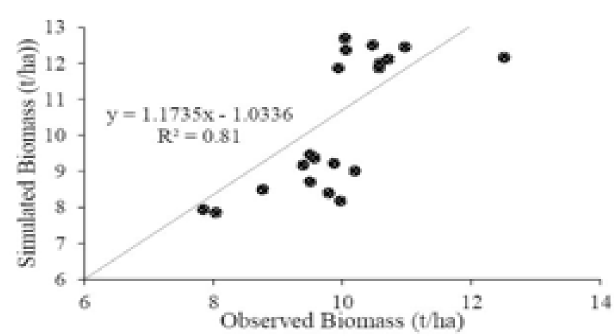

Fig. 7. Calibration results of biomass yield under all irrigation and nitrogen levels.

Table 4. Calibration results of model under varying water and nitrogen fertilizer treatments in 2012.

Treatment	(%±) Pe	Biomass (t ha^{-1})		P_e (%±)	Yield (t ha^{-1})	
		Sim	Obs		Sim	Obs
			N_1 = no nitrogen			
W_1	16.50	9.79	8.40	10. 80	3.27	2.95
W_2	13.90	9.90	8.71	8.27	3.55	3.87
W_3	12.90	10.19	9.02	8.13	4.05	4.42
W_4	11.90	10.97	12.46	8.65	4.35	4.76
W_5	7.10	12.51	13.17	4.14	4.28	4.11
W_6	11.20	11.54	13.00	6.35	4.17	3.92
			N_2 = 33% nitrogen req.			
W_1	13.70	6.85	7.94	17.55	3.08	2.62
W_2	11.34	10.13	9.17	8.17	3.37	3.67
W_3	12.80	10.57	9.37	3.89	3.80	3.96
W_4	9.90	10.58	12.00	5.18	4.27	4.51
W_5	8.50	13.24	14.46	4.38	3.80	3.65
W_6	11.85	12.94	14.68	6.51	4.42	4.15
			N_3 = 66% nitrogen req.			
W_1	15.70	9.47	8.18	11.57	2.70	2.42
W_2	14.30	9.77	8.50	8.95	3.48	3.21
W_3	7.20	11.54	10.71	8.35	4.01	3.70
W_4	5.60	12.57	11.87	5.04	4.38	4.17
W_5	4.71	12.54	13.16	3.03	4.40	4.30
W_6	6.90	9.87	9.23	6.34	4.02	3.84
			N_4 = full nitrogen, 100% nitrogen req.			
W_1	15.01	9.04	7.86	8.13	3.18	2.94
W_2	8.40	9.95	9.18	5.60	3.73	3.97
W_3	13.70	10.24	11.87	6.00	3.96	4.21
W_4	11.40	10.73	12.12	3.39	4.15	4.32
W_5	7.70	12.47	13.51	2.12	4.12	4.04
W_6	9.80	12.06	13.37	3.57	4.05	3.82

Table 5. Comparison of calibration results of model under varying irrigation regimes.

Treatment	Yield (t ha^{-1})		Error	Biomass (t ha^{-1})		Error
	Observed	Simulated	(±%)	Measured	Simulated	(±%)
Rainfed (W_1)	2.73	3.06	10.78	8.09	8.79	7.96
W_2 (33%FC)	3.68	3.53	4.25	9.94	8.89	10.50
W_3 (66% FC)	4.07	3.90	4.36	10.24	10.64	3.70
W_4 (88% FC)	4.44	4.28	3.83	12.11	11.21	8.00
W_5 (100% FC)	4.025	4.15	3.01	13.56	12.69	6.80
W_6 (125%FC)	3.93	4.17	5.76	12.57	11.60	8.40

The relation between the simulated and the measured yield and biomass were linear with R^2 values of 0.88 and 0.81 (Figs. 6 and 7). The same results were also reported by Aziz et al. (2022) for cotton under varying deficit irrigation treatments in Punjab, India where the AquaCrop model that simulated biomass and yield was consistent with the measured values with R^2 of 0.976 and 0.950, respectively.

Validation of the AquaCrop Model

The calibrated model was validated using data from 2013 and 2014. No significant differences were observed between the data sets obtained through the two consecutive years of research. Virtually, the validation runs with the calibrated model for cotton showed good results for the simulated yield as indicated by R^2 and RMSE values in Figs. 8 and 9 (R^2 = 0.89 and 0.90; RMSE = 0.32 and 0.27 in 2013) for yield and biomass, respectively. Moreover, these values were obtained for biomass prediction at the rate of 0.983 and 0.977, for slope and R^2 in 2013 and 2014, respectively (Figs. 10 and 11). The model could accurately reproduce cotton yields and WP for different modelled cotton yields with the Farahani et al. (2009) model and found a similarity between observed and simulated data. Hence, in cases of limited input parameters and for management targets, using a simple model such as AquaCrop should be recommended.

Table 6. Statistical tests to compare simulation and actual results for calibration.

Parameter	(%) Er	AAD	E	RMSE
Yield	8.08	0.08	0.80	0.34
Biomass	14.62	1.90	0.88	2.61
HI	24.65	0.071	-	0.084

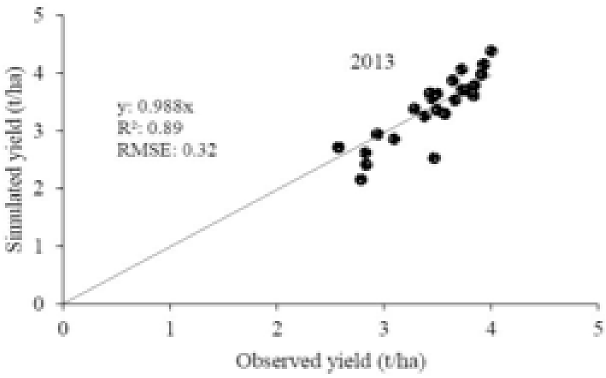

Fig. 8. Validation results for cotton yield under all irrigation and nitrogen levels in 2013.

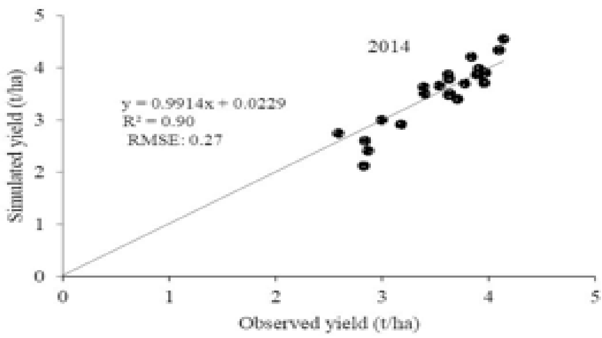

Fig. 9. Validation results for cotton yield under all irrigation and nitrogen levels in 2014.

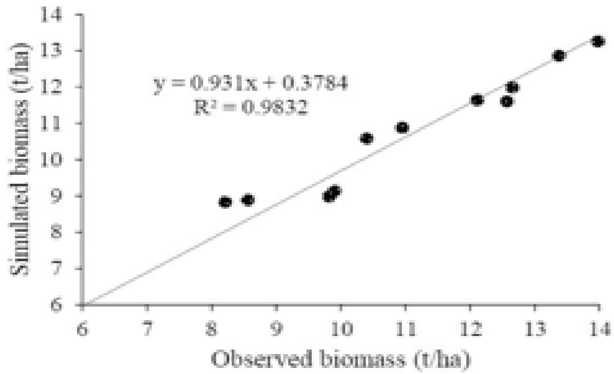

Fig. 10. Validation results for biomass under all irrigation and nitrogen levels in 2013.

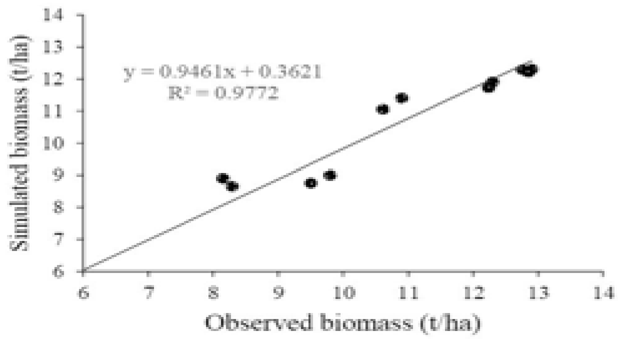

Fig. 11. Validation results for biomass under all irrigation and nitrogen levels in 2014.

The best-validated AquaCrop model was achieved with estimation errors ranging from the lowest value of 2.24% for W5 to the highest value of 8.15% in W6 with all nitrogen levels in 2013 (Table 7). Similarly, the maximum (8.9%) and the minimum P_e (2.97%) for yield were obtained for the W3 treatment and full irrigation treatment (W5) in the season of 2014, respectively (Table 8). The model was validated for simulation of yield and biomass for all treatment levels in the P_e statistics $0.8 < E < 0.93$, $0.27 < RMSE < 0.58$ t ha^{-1}, $0.08 < AAD < 1.9$, and $8.08 < MAE < 14.62\%$. The results of the model evaluation are indicated in Table 9.

Table 7. Comparison of validation results of model under all irrigation treatments in 2013.

Treatment	Yield (t ha^{-1})		Error	Biomass (t ha^{-1})		Error
	Observed	Simulated	(±%)	Observed	Simulated	(±%)
Rainfed (W_1)	2.93	2.73	7.32	8.21	8.83	7.02
W_2 (33% FC)	3.49	3.29	6.08	9.82	9.08	8.35
W_3 (66% FC)	3.21	3.02	6.29	10.40	10.85	4.15
W_4 (88% FC)	3.62	3.76	3.73	12.11	11.64	4.01
W_5 (100% FC)	3.64	3.56	2.24	13.37	12.86	3.81
W_6 (125% FC)	3.85	3.56	8.15	12.57	11.60	8.36

The same results were reported by Aziz et al. (2022) for cotton at Barani Agricultural Research Institute, Pakistan. In this study, AquaCrop's performance was evaluated by simulating biomass accumulation and WP. The amounts of Willmott's index of agreement (d) and RMSE showed that model predictions are suitable for non-stressed and moderately stressed conditions.

Table 8. Comparison of validation results of AquaCrop under all irrigation levels in 2014.

Treatment	Yield (t ha^{-1})		Error	Biomass (t ha^{-1})		Error
	Observed	Simulated	(±%)	Observed	Simulated	(±%)
Rainfed (W_1)	3.02	2.89	4.50	8.15	8.90	8.42
W_2 (33% FC)	3.13	3.02	3.00	9.50	8.75	8.57
W_3 (66% FC)	3.42	3.14	8.90	10.61	11.05	4.00
W_4 (88% FC)	3.76	3.92	4.10	12.24	11.72	4.43
W_5 (100% FC)	3.81	3.70	2.97	12.76	12.28	3.91

Table 9. Statistical tests to compare simulation and actual results.

Parameter	MAE (%)	E	AAD	RMSE (t ha^{-1})
Yield	8.08	0.93	0.08	0.27
Biomass	14.62	0.85	1.90	0.58
HI	24.65	0.80	0.071	0.084

CONCLUSION

The AquaCrop model's performance for cotton was evaluated in a semi-arid environment. AquaCrop calibrated for cotton yield under full irrigation and all nitrogen levels resulted in prediction errors (P_e) ranging from 2.12% to 17.5%. Moreover, the model simulated biomass under 100% water requirement (WR) with the lowest P_e of 4.7%, whereas the non-irrigated treatment exhibited the highest P_e of 16.5%. Model calibration results for cotton yield and biomass for all treatments were the P_e values of $0.8 < E < 0.88$ and $0.34 < RMSE < 2.61$ t ha^{-1}. Also, the validation results were in line (i.e., $0.85 < E < 0.93$ and $0.27 < RMSE < 0.57$ t ha^{-1}) with the measured data for all treatments during 2014. Results showed that the model was more precise in estimating cotton yield under 100% and 88% WR compared to the non-irrigation and 33% WR treatments. Overall, the AquaCrop model can be used to estimate cotton growth with acceptable accuracy under variable irrigation and field management situations in the semi-arid regions of northern Iran.

REFERENCES CITED

ABEDINPOUR M, SARANGI A, RAJPUT T, SINGH M, PATHAK H. 2012. Performance evaluation of AquaCrop model for maize crop in a semi-arid environment. [dissertation]. New Delhi: Indian Agricultural Research Institute.

ASGHAR N, AKRAM NA, AMEER A, SHAHID H, KAUSAR S, ASGHAR A, IDREES T, MUMTAZ S, ASFAHAN HM, SULTAN M, JAHANGIR I. 2021. Foliar-applied hydrogen peroxide and proline modulates growth, yield and biochemical attributes of wheat (*Triticum aestivum* L.) under varied N and P levels. Fresen Environ Bull. 30(5):5445–5465.

AZIZ M, RIZVI SA, SULTAN M, BAZMI MSA, SHAMSHIRI RR, IBRAHIM SM, IMRAN MA. 2022. Simulating cotton growth and productivity using AquaCrop model under deficit irrigation in a semi-arid climate. Agric. 12(2):242. doi:10.3390/agriculture12020242.

FARAHANI HJ, IZZI G, OWEIS TY. 2009. Parameterization and evaluation of the AquaCrop model for full and deficit irrigated cotton. Agron J. 101(3):469–476. doi:10.2134/agronj2008.0182s.

FERERES E, SORIANO A. 2007. Deficit irrigation for reducing agricultural water use. J Exp Bot. 58(2):147–159. doi:10.1093/jxb/erl165.

HSIAO TC, HENG L, STEDUTO P, ROJAS-LARA B, RAES D, FERERES E. 2009. AquaCrop—the FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. Agron J. 101 (3):448–459. doi:10.2134/agronj2008.0218s.

HUSSEIN F, JANAT M, YAKOUB A. 2011. Simulating cotton yield response to deficit irrigation with the FAO AquaCrop model. Span J Agric Res. 9(4):1319–1330. doi:10.5424/sjar/20110904-358-10.

KALBALI E, ZIAEE S, NAJAFABADI MM, ZAKERINIA M. 2021. Approaches to adapting to impacts of climate change in northern Iran: the application of a Hydrogy-Economics model. J Clean Prod. 280(Part 1):124067. doi:10.1016/j.jclepro.2020.124067.

NUNES HGGC, FARIAS VDS, SOUSA DP, COSTA DLP, PINTO JVN, MOURA VB, TEIXEIRA EO, LIMA MJA, ORTEGA-FARIAS S, SOUZA PJOP. 2021. Parameterization of the AquaCrop model for cowpea and assessing the impact of sowing dates normally used on yield. Agri Water Manag. 252:106880. doi:10.1016/j.agwat.2021.106880.

RAES D, STEDUTO P, HSIAO TC, FERERES E. 2009. AquaCrop—the FAO crop model to simulate yield response to water: II. Main algorithms and software description. Agron J. 101(3):438–447. doi:10.2134/agronj2008.0140s.

RAES D, STEDUTO P, HSIAO TC, FERERES E. 2012. Crop water productivity. Calculation procedures and calibration guidance. AquaCrop version 4.0. Land and Water Development Division, Rome: Food and Agriculture Organization of the United Nations. https://www.fao.org/fileadmin/user_upload/faowater/docs/AquaCropV40Chapter3.pdf.

STEDUTO P, HSIAO TC, RAES D, FERERES E. 2009. AquaCrop—the FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agron J. 101(3):426–437. doi:10.2134/agronj2008.0139s.

TODOROVIC M, ALBRIZIO R, ZIVOTIC L, SAAB MTA, STOCKLE C, STEDUTO P. 2009. Assessment of Aqua Crop, CropSyst, and WOFOST models in the simulation of sunflower growth under different water regimes. Agron. J. 101(3):509–521. doi:10.2134/agronj2008.0166s.

[UNESCO-WWAP] UNESCO World Water Assessment Program. 2006. Water: a shared responsibility; the United Nations World Water Development Report 2. Paris (France): United Nations Educational, Scientific and Cultural Organization and New York (NY): Berghahn Books.