Original Research

Irrigated Silage Maize Yield and Water Productivity Response to Deficit Irrigation in an Arid Region

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Abstract

Simulation models have proven to be useful. The AquaCrop model, which has been expanded by FAO, simulates crop yield based on the applied water under conditions of full and deficit irrigation levels. In this study, the AquaCrop model's performance was tested using data for silage maize (*Zea mays* L.) under full (100% fulfillment of ET_c) and deficit irrigation levels (90, 80, 70, and 60% of full irrigation) in the arid and semiarid environment of central Iran in the Gavkhuni River Basin (GRB). To calibrate this model, we used physiological measurement sets of cropping seasons 2000 to 2002. AquaCrop simulated well the decrease of the biomass yield (B-yield) of silage maize in response to drought as happened in the field. B-yield was decreased by 9.9% under deficit irrigation as compared to fully irrigated conditions. The coefficient of determination (R^2) for simulation of B-yield and water productivity (WP) was 0.95 and 0.99, respectively. But the R^2=0.77 was not satisfactory for actual evapotranspiration (ETa). The results for all investigated parameters in the three years showed that RMSE, d, ME, CRM, and E values ranged from 0.90% to 3.85%, 0.98 to 1, 1.25% to 6.4%, -0.027 to 0.03, and 0.817 to 100%, respectively. At the end, a local second-degree polynomial crop water production function (CWPF) for silage maize is presented.

Keywords: deficit irrigation, silage maize, simulation model, biomass yield, Gavkhuni River Basin (GRB)

Introduction

Agriculture in Iran is highly dependent on irrigation water, as about 70% of the agricultural products come from irrigated crops [1]. In Iran, the grass conserved as silage is the most noticeable source of winter forage available for feeding dairy cattle. Planting this crop after wheat and barley is common in some parts of the country (e.g. Isfahan, which is located in the Gavkhuni River Basin (GRB)) [2]. Water supply uncertainty and financial constraints in arid regions are the two important issues that farmers are subjected to. These problems are especially severe in the case of summer crops, such as silage maize, grown during June to October and has high water requirement. Therefore, there

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is an increasing competition for water to obtain maximum production. The only way to keep supply and demand in balance in GRB is to reduce allocations to agriculture. Improving WP, based on more production per unit of water used in agriculture, is vital [3]. Gheysari et al. [4] focused on the response of silage maize to variable irrigation under arid and semi-arid conditions in Iran. Their results showed that the biomass of maize was increased as a function of the amount of applied water. Bekele and Tilahun [5] revealed that all deficit irrigations increased the water use efficiency of onion from a minimum of 6% by stressing the crop during the first growth stage to a maximum of 13% by partially stressing the crop at 75%ETc of the optimum application throughout the growing season. The main advantage of using a crop yield model is the capability of predicting crop yield in response to deficit irrigation levels so that field expenses can be saved to collect the experimental data. Many complicated growth models have focused on maize in water-scarce areas. Some of these models have not yet been tested under deficit irrigation in arid conditions. Some widely acceptable maize models are Hybrid model, CERES [6], and DSSAT, which simulate the growth of maize crop under water-limited conditions [7]. Nearly all these models are complicated and require a large number of parameters. Cavero et al. [8] believes that the CROPWAT model should be used with caution due to mal-adaptation of simulated and observed evapotranspiration.

AquaCrop is a crop growth model, developed by FAO, that resulted from the revision of Irrigation and Drainage Paper No. 33 [9] by differentiating the ETa into non-benefitial soil evaporation (Ea) and transpiration (Tr). Detailed description of the model is given by Steduto et al. [10]. One of the important key features of AquaCrop is that the simulation takes into account harvest index response to water stress.

To date, no study has been reported in the literature on simulation of deficit irrigation of silage maize with AquaCrop. Therefore, some of the previous researches about other crops are presented as follows. Farahani et al. [11] investigated the application of AquaCrop model for cotton under full and deficit irrigation regimes in Syria. They suggested that the key parameters for calibration must be tested under different climates, soils, cultivars, irrigation methods, and field managements. Hsiao et al. [12] showed that transpiration efficiency is well-simulated by AquaCrop for fully irrigated scenarios. Many researchers have applied the AquaCrop model to evaluate the effect of changes in the quantity of irrigation water for cotton, quinoa, corn, sunflower, cotton, and maize in Syria, Bolivia, Spain, Italy, Spain, and the United States. All this research showed that the AquaCrop is a good model for scenario analysis to improve WP [11-16].

In the present study, we focused on deficit irrigation scenarios for silage maize, at Nekuabad irrigation network, GRB, Isfahan province, Iran. The objectives of this study were to determine the following:

i) simulation of silage maize B-yield,
ii) ETa simulation,
iii) WP and local CWPF.

This paper also presents the calibration and validation results of AquaCrop model for the simulation of crop parameters.

Experimental Procedures

Study Area

The Nekuabad irrigation network consisting of left and right bank schemes in the Lenjanat District of Isfahan province is located in GRB, Iran. The experiment was performed at the Agricultural Research Center, Najafabad, Iran, located at 32º38' N latitude, 51º22' E longitude and 1,649 m elevation. The site is characterized by an arid climate with a rainy season from fall to early spring, averaging 130 mm, with no rainfall during the summer.

Description of Experimental Treatments

The essential experimental data for model validation were available from an irrigation study at Najafabad Research Station [17]. The experiment was conducted with irrigation factor in 5 levels and 3 replicates. The levels of irrigation water included: 100%, 90%, 80%, 70%, and 60% of full water requirement. The effects of various levels of consumptive water levels on yield of maize was studied based on randomized complete blocks design as a split plot layout for 3 years (2000 to 2002). The maize was sown by hand at 5-6 cm depth at the end of May. The row spacing and crop distances on each row were 75 cm and 20 cm, respectively, giving a plant density of 90,000 plants·ha^{-1}. The length of each row was 30 m and there were four rows in each plot. The type and amount of the required fertilizers were determined from the analysis of soil samples based on instructions of the Soil and Water Research Institute [18]. The amount of nitrogen (N) application was 500 kg·ha^{-1} N (urea with 46% N), which was divided into 3 applications (10 days before planting, 30 days after planting, every 15 days until 22 July). Ammonium phosphate (P) and potassium sulfate (K) were added to the soil at a rate of 250 and 350 kg·ha^{-1}, respectively. Pests and weeds were controlled following the recommendations given by Isfahan Pest Management Department. Since the model uses canopy ground cover instead of LAI, canopy cover was monitored at every 15 to 20 day intervals using a grid system and canopy meter.

At harvest, the final total biomass per plot was determined. At the end of September, treatments were compared based on dry biomass and volume of applied water. Results were subjected to ANOVA to analyze the effects of treatments and their interactions. In order to determine the effects of year on yield, the obtained data were analyzed using compound variance analysis, and the averages of different treatments were separated using Duncan Multiple Range Test and SAS software (SAS Institute, Inc., Cary, NC). A probability level of 0.05 (5%) was selected. Irrigation intervals were seven days, which was based on the existing water rights in the region and also is in accordance with irrigation scheduling. The levels of irrigation water were applied based on the volumetric basis using siphons (2.54 cm diameter). The first irrigation by furrow irrigation method was implemented one day after seeding, with observed emergence about 6 days later. The source of water supply was from an irrigation canal. The EC, SAR, and PH of irrigation water were 3.4 $dS \cdot m^{-1}$, 3.5, and 7.2, respectively. Soil salinity was measured to be 4.4 $dS \cdot m^{-1}$. During the experiment there was a severe drought in the region and the whole country and rainfall declined to 48 and 70 mm in 2001 and 2002, respectively.

Irrigation Application

There were 13-15 different irrigation applications that were imposed in weekly intervals from 1 day after planting until 10 days prior to harvest that took place 100-114 days after sowing. The total water applied through irrigation during the whole season in selected irrigation treatments (fully irrigated T1, and deficit irrigated T2 to T5). These values were 985 mm (T1), 886 mm (T2), 788 mm (T3), 689 mm (T4), and 591 mm (T5) in 2000, in 2001 they were 939 mm (T1), 844.5 mm (T2), 751.1 mm (T3), 657.3 mm (T4), and 563.4 mm (T5); and in 2002 were 1055 mm (T1), 949.5 mm (T2), 844 mm (T3), 738.5 mm (T4), and 633 mm (T5).

Estimation of ET_o

We used ET_o calculator (Version 3, January 2009) for accounting of ET_o based on long-term weather data (1979-2007) from Najafabad station. In this study, FAO Penman-Monteith approach [19] was utilized for ET_o computation. Daily weather data, including maximum and minimum air temperature, maximum and minimum relative humidity, sunshine hours, and wind speed were collected from the station (Fig. 1). The maize growing season in the study area is typically during hot months of the year with high evaporative demand of about ET_o ~13.6 $mm \cdot d^{-1}$ (Fig. 2).

Simulative Capabilities of the AquaCrop Model

From the outset, this study had as a specific objective the utilization of green crop simulation and to support this with extensive use of a new crop model. AquaCrop model, version 3.1, simulates the progression of green canopy cover (CC), aboveground biomass with time, water productivity, and soil water content (SWC) with some attention to evapotranspiration using a step-wise approach. The simulations in the present study were mainly focused on B-yield, Eta, and WP.

Model Input Data

The local inputs such as weather data, irrigation schedule, and sowing density were obtained from corresponding Iranian organizations, although some default values are provided for maize [12]. In AquaCrop, the inputs were saved in climate, crop, soil, and management files. Those parameters that did not change with time (such as climate and management practices), were named as constant. In order to run the model, we collected cultivar-specific parameters that were referred to user parameters. User-specific parameters were estimated by judging, and 21 of the conservative crop parameters were used from the study of

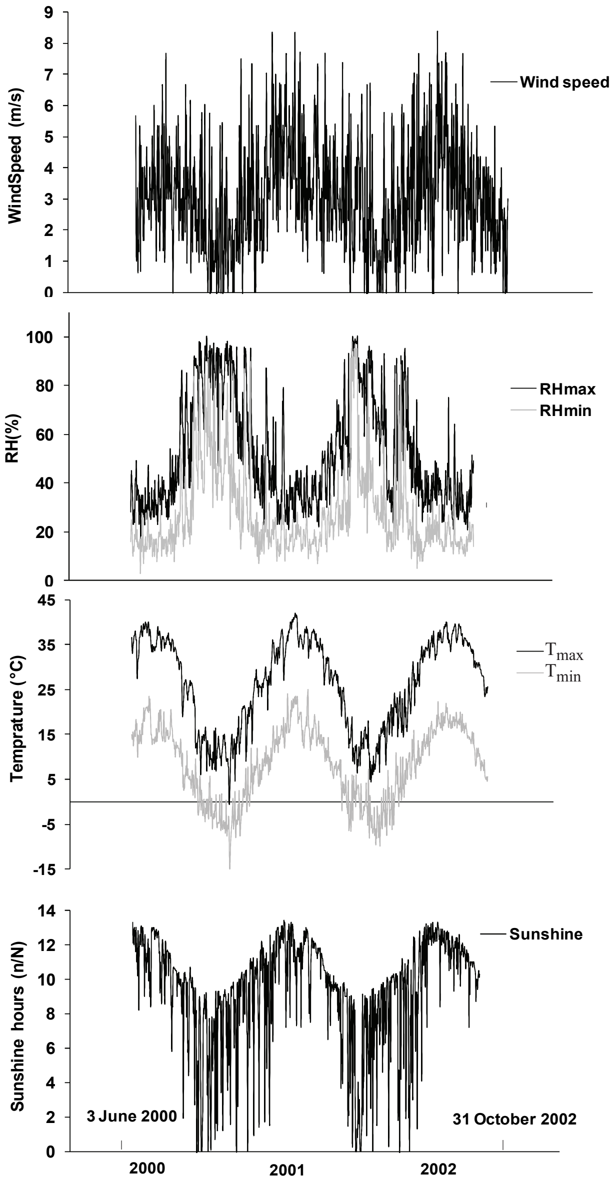

Fig. 1. Measured daily meteorological variables for 2000-02.

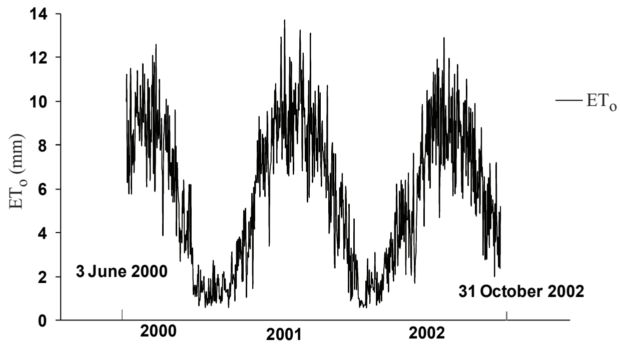

Fig. 2. ET_o computed from daily meteorological data using the Penman-Monteith equation.

Hsiao et al. [12]. Soil physical characteristics [soil depth (1 m), soil texture (silty clay loam), soil moisture at saturation (47%), field capacity (FC=38%), permanent wilting point (PWP=19%), in volumetric basis bulk density (1.42 g·cm^{-3}), and saturated hydraulic conductivity (K_{sat}=300 mm·day^{-1})] at field site were measured either directly or in the Isfahan Soil and Water Laboratory. Soil water content in the root zone was recorded throughout the season using gravimetric soil sampling.

Results and Discussion

Calibration of AquaCrop for Silage Maize

To calibrate the model, results from the research project were used [17]. In particular, the following crop growth parameters were analyzed:

i) B-yield,
ii) ETa
iii) WP

Calibration of the simulated parameters was performed and the results are shown in Figs. 3-5. Output data from the experiment, and meteorological data, were the inputs for calibration of the model. For each of the simulation runs, weather data, soil characteristics, irrigation depths, sowing date, and planting density were entered as inputs. The parameters such as cultivars, local plant density, measured maximum rooting depth, and time of crop development were used for model calibration. These data were collected for 2000, 2001, and 2002 growing seasons. The crop parameters used in this study are presented in Table 1. Model run for irrigation treatments (T1 and T5) and determination of simulated yields in different treatments by repetition of phonologic stages, crop growth rates, and conservative (constant). Changing basic crop coefficient (K_{cb}) during crop growth to match simulated yield with actual yield. The parameters were changed manually around the default values until the best fitting with measured data was achieved. Since the best values of conservative parameters obtained from calibrating the model were close to Hsiao et al. [12], they were selected as the input parameters, except K_{cb}, in which it was taken as 1.1 to obtain higher yields and water productivity. The reason for selecting K_{cb} was that it was one of the most important parameters for simulation of evapotranspiration. Seven indices, including coefficient of determination (R^2), efficiency (E), root mean squared error (RMSE), maximum error (ME), compatibility (d), coefficient of residual mass (CRM), and deviation percent, were used to compare simulated and measured values for the calibration of AquaCrop model in Table 2 [20]. The agreement between simulated and measured B-yield and ETa were good for different water stress treatments. By contrast, calculated WP exceeded simulated WP for T1 and T5 treatments (ME=4.22%, Table 2).

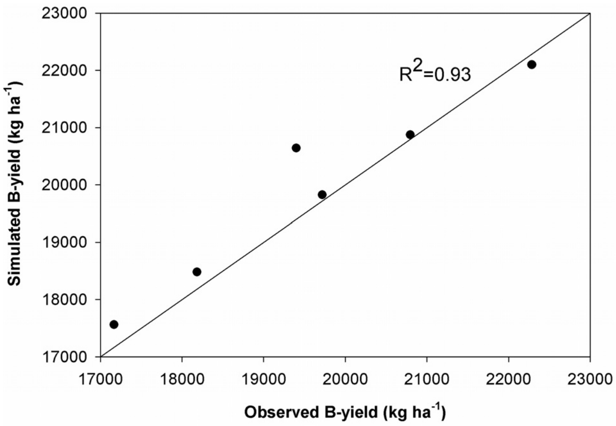

Fig. 3. Simulated vs. observed values of silage maize B-yield for model calibration.

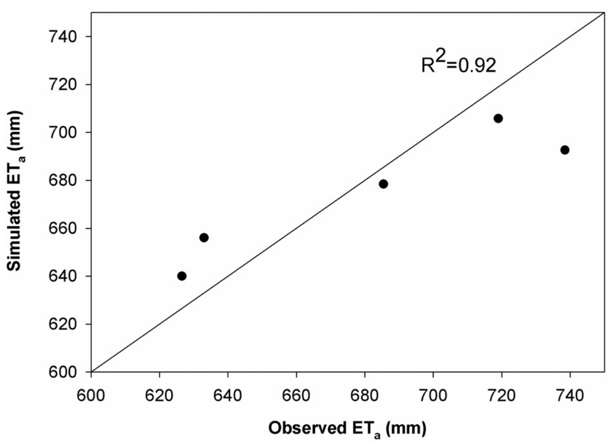

Fig. 4. Simulated vs. observed values of silage maize evapotranspiration for model calibration.

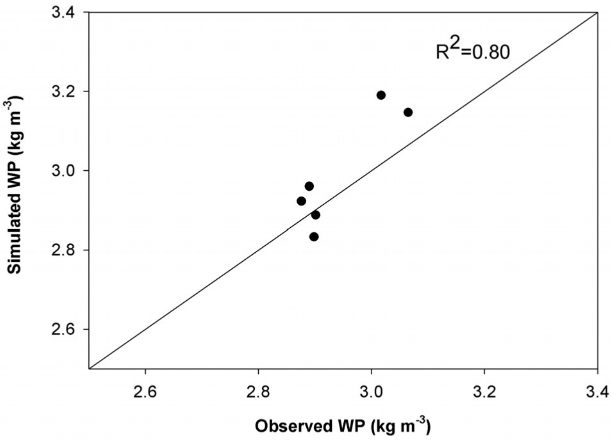

Fig. 5. Simulated vs. observed values of silage maize water productivity for model calibration.

Validation of AquaCrop for Silage Maize

The model was validated for regulated deficit irrigation conditions (treatments T2-T4). B-yield, ETa, and WP were simulated for different treatments using the calibrated model. The statistics for comparison between observed and simulated values of B-yield, ETa, and WP for validation of AquaCrop model are presented in Table 3. The R^2 index shows good correlation between simulated and measured

Table 1. AquaCrop model parameters for silage maize simulation for 3 years at GRB.

Parameter	Value	Units	Method of determination
Normalized crop water productivity (wp*)	33.7	g/m^3	Estimated
Threshold for stomatal closure (P_{upper})	0.09	-	Calibrated
Maximum root depth	0.85	M	Measured
Initial canopy cover (CC_0)	4.5	%	Estimated
Maximum canopy cover (CC_x)	96	%	Measured
Canopy growth coefficient (CGC)	15.9	%	Calibrated
Canopy decline coefficient (CDC)	12.6	%	Calibrated
Leaf growth threshold (p_{upper})	0.14	-	Calibrated
Leaf growth threshold (P_{lower})	0.72	-	Calibrated
Senescence stress coefficient (P_{upper})	0.69	-	Calibrated
Base temperature	8	C	Estimated
Upper temperature	30	C	Estimated
Evapotranspiration crop coefficient	1.1	-	Default
Reference harvest Index	94	%	Measured
Time to reach crop germination	7	DAS[a]	Estimated
Time to reach full max canopy cover	65	DAS	Estimated
Time to reach maturity	105	DAS	Estimated
Time to reach flowering	57	DAS	Estimated

[a]Days after sowing

Table 2. Statistical indices derived for evaluating the performance of AquaCrop model in simulating biomass yield, evapotranspiration, and water productivity for calibration.

Statistical Index	R^2	E	RMSE	ME	d	CRM	Deviation (%)
B-yield	0.93	0.89	2.82	2.91	0.99	-0.02	1.73
Eta	0.92	0.99	3.78	3.17	1	0.00	0.23
WP	0.80	1	3.04	4.22	1	-0.02	1.61

Table 3. Statistical indices derived for evaluating the performance of AquaCrop model in simulating biomass yield, evapotranspiration, and water productivity for validation.

Statistical Index	R^2	E	RMSE	ME	d	CRM	Deviation (%)
B-yield	0.95	0.817	1.93	3.67	0.99	-0.019	1.42
ETa	0.77	0.99	2.63	4.35	o.98	0.03	-1.33
WP	0.99	1	2.33	3.67	1	-0.025	1.45

B-yields and WP for three years of the experiment. The R^2 value for ETa was 0.77. The E values that show the efficiency of the model for B-yield, ETa, and WP were 0.817, 0.99, and 1.0, respectively. The highest model efficiency was for WP. Low value of efficiency for B-yield was due to high irrigation water stresses. The simulated yield showed a reduction of yield with decreasing irrigation water depth. The model simulated the yield fairly well when irrigation treatment changed from 70% to 100%. The lowest RMSE was for B-yield, which is a good sign of model simulation. The higher RMSE values belonged to WP and ETa. The lowest ME (3.67) was for B-yield and WP, and shows that AquaCrop simulates maize yield and water productivity better than ETa. This index was 6.39 for B-yield in 60%

irrigation treatment of the third year. The d index is near 1.0 for the three evaluated parameters. This index shows good correlation between irrigation water deficit and reduction of simulated yield. The CRM index presents model tendency to over-estimation or under-estimation of the measured values of studied parameters. Its value is -0.019 and 0.025 for B-yield and WP, respectively. The negative CRM shows that the model over-estimates yield and WP in most cases. Positive values of CRM for evapotranspiration shows that the model under-estimates this parameter. With regards to water scarcity in Iran, this will lead to important water savings. Index of percent deviation shows that the model over-estimated B-yield by 1.42% and WP by 1.45%, and under-estimated ETa by -1.33%.

All the above-mentioned indices show good simulations by the AquaCrop model in the study area. Therefore, with regards to the results of calibration, validation, and evaluation of the AquaCrop model, it could be concluded that this model simulates B-yield, WP, and ETa very well for deficit irrigation of silage maize in the central region of Iran. Hsiao et al. [12] in an experiment on maize found that for 100% water requirement treatment, d index was 0.93-0.98, which is very close to our results. In their experiment, deviation of simulated from measured yield was 1-23.8%.

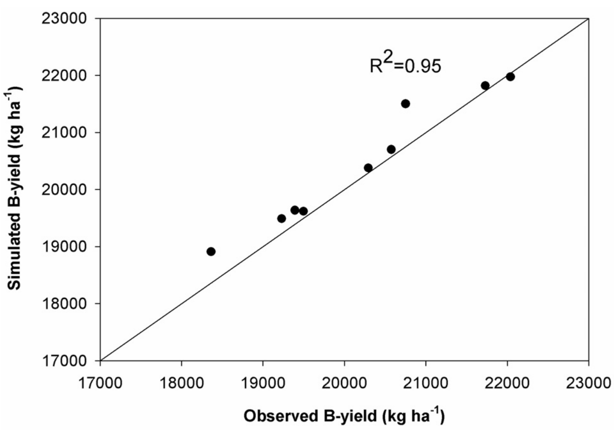

Fig. 6. Simulated vs. observed values of silage maize B-yield for model validation.

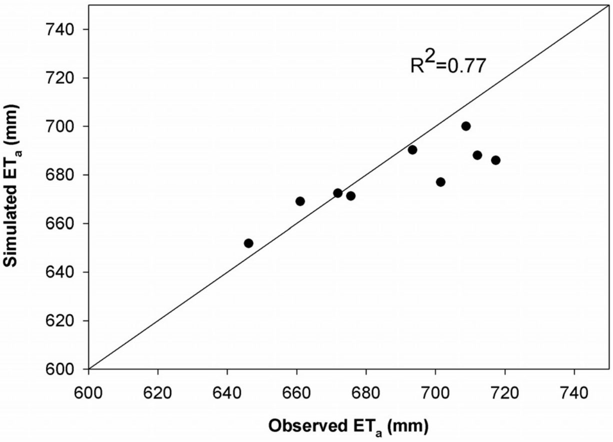

Fig. 7. Simulated vs. observed values of silage maize evapotranspiration for model validation.

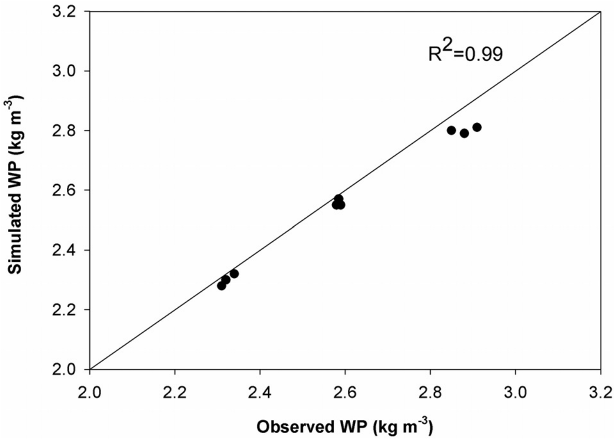

Fig. 8. Simulated vs. observed values of silage maize water productivity for model validation.

Heng et al. [14] showed that AquaCrop predicts yield very well under full irrigation water supply or moderate stress (deviation <5%, RMSE=0.8-5.61%), but the model's performance was not desirable in highly stressed treatments, which again is similar to the results of the present study. Simulated B-yield is shown against measured values in Fig. 6. This figure shows that although the predicted B-yield is close to measured values, the model has over-estimated it. This result is similar to other findings [12-14, 16]. The simulated ETa was not in good agreement with the measured values (Fig. 7), but WP values were close to those calculated (Fig. 8). The small differences (especially in T4 and T5 treatments) could be attributed to the fact that soil and water salinity was not taken into consideration in the AquaCrop model.

Sensitivity Analysis

The inputs for sensitivity analysis in the present research are agronomic data, soil, meteorology, and irrigation management data. In order to compare the model outputs, the inputs were changed on the order of ±25% in each step. In this regard, Abbasi [21] states that selection of percent change in the inputs is somewhat arbitrary (in the range of 25, 50, 75, etc., percent) and it depends on limits of parameters, sensitivity of the model to different parameters, and convergence rate of the model. After changing the values of input parameters, the model outputs were compared with the original outputs. The computed sensitivity coefficients were compared for a range of variation in input parameters, and are presented in Table 4. The results showed that the most sensitive agronomic parameter in AquaCrop model is time to senescence. It should be noted here that over-estimation of the beginning of maturity causes less error in yield prediction than under-estimation of this phenomenon. However, the model showed less sensitivity to time of seed emergence, length of flowering period, days to maximum root growth, planting density, and days to flowering. Also, the sensitivity of the model to variations in basic crop coefficient (K_{cb}), canopy-cover growth (CGC),

Table 4. Sensitivity coefficient (Sc) of AquaCrop for silage maize model calibration.

Input parameters		Sc (+25%)	Sc (-25%)	Sensitivity level
Crop inputs	Crop coefficient for transpiration	0.57	1.03	Moderate
	Plant density	0.08	0.1	Low
	Canopy growth coefficient	0.97	0.51	Moderate
	Crop water productivity	0.99	0.43	Moderate
	Reference harvest index	-	0.98	Moderate
	Time to canopy senescence, DAS	0.53	3.5	High
	Time to emergence, DAS	0	0	Not sensitive
	Time to flowering, DAS	0.17	0.09	Low
	Length of the flowering stage	0	0	Not sensitive
	Time to maximum rooting depth, DAS	0.02	0.01	Low
	Rooting depth	0.02	0.09	Low
Initial soil water content	Full irrigation	0	0	Not sensitive
	90% and 80% full irrigation	0	0.22	Low
	70% and 60% full irrigation	0	1.5	High
Initial soil condition	Hydraulic conductivity	0	0.01	Low
Irrigation	Full irrigation	0	0.06	Low
	90% full irrigation	0.01	0.07	Low
	80% full irrigation	0.05	0.31	Moderate
	70% full irrigation	0.08	1.16	Moderate
	60% full irrigation	0.36	1.56	High

normalized water productivity (WP*), reference harvest index (HI_0), and initial soil moisture content in deficit irrigated treatments was greater than the rest of the parameters. The sensitivity of the model to depth of irrigation water was different in different irrigation treatments. The model's sensitivity increased with decreasing the irrigation depth. For example, as irrigation water depth increases, water productivity decreases; therefore, in a specific irrigation water depth, sensitivity to a change of -25% is more than a change of +25%. In general, model outputs were highly sensitive to the depth of irrigation water, initial soil moisture content in water-stressed treatments, and time of maturity.

Crop-Water-Production Function (CWPF)

CWPFs express the quantitative relationships between crop yield and production inputs (irrigation water quantity and quality, soil, fertilizers, energy, etc.). For maize grown in different areas, linear and second-degree polynomial CWPFs are mostly reported [22]. The mathematical functions of ET and yield that better fit the production with irrigation water volume have been second-degree polynomials [23]. Also, Shani and Dudley [24] used polynomial functions and found a relationship between maize yield and water use (R^2>0.9) that was very useful in the application of deficit irrigation. It is noted that there is no CWPF universally applicable to all crops, growing seasons, and climatic zones, and this is the reason for the CWPFs being influenced by crop and local conditions. There is therefore the need to establish the CWPF using AquaCrop model. We showed that AquaCrop simulated the silage maize yield response to irrigation water successfully (Fig. 9). The R^2 of the regressed equation was 0.962, which shows high corre-

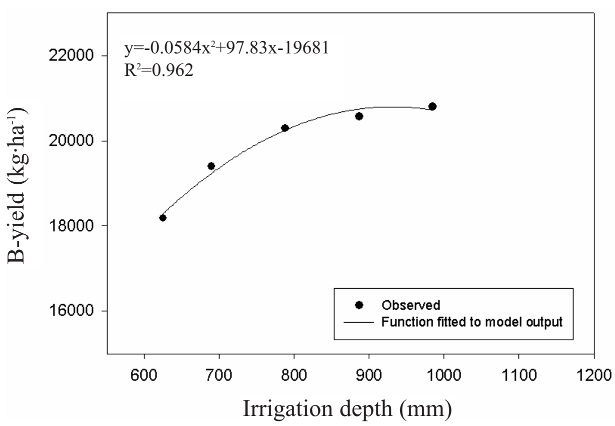

Fig. 9. Local yield-water production function.

lation between these two parameters. The derived CWPF ranges for the 12 model outputs denoted by high R^2 are 625-985 mm applied irrigation water. The data points obtained by varying the seasonal water were used to generate the response function. The CWPF was investigated by five irrigation water treatments (observed data) ascribed to: (990, 20796), (862, 20574), (794, 20292), (694, 19392), and (605, 18182) mm and kg·ha^{-1}, respectively. This second-order production function is recommendable in the study region.

Conclusions

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 B-yield of silage maize for fully supplied irrigation or treatments with some water stress; but under severe water stress (60% of full irrigation), the model performed less satisfactorily. In other words, the model underestimates the effect of water stress. According to the validation results, the calculated E, RMSE, ME, d, and CRM values were 0.817, 1.93%, 3.67%, 0.99, and -0.019 for B-yield, 0.99, 2.63%, 4.35%, 0.98, and 0.03 for ETa, and 1, 2.33%, 3.67%, 1 and -0.025 for WP, respectively. The R^2 values were higher than 0.95 for the evaluated parameters (except the ETa). Generally, crop yield depends on many factors, including soil fertility, amount and time of fertilizer application, and soil and water salinity. But these parameters are not dealt with in AquaCrop. Therefore, this model is not recommended under saline conditions. Since irrigation water is mostly saline at downstream of the GRB, then deficit irrigation will be a disaster in the long run. Thus, for sustainable agriculture in the area, monitoring of soil moisture and salinity is a necessity for better management of irrigation water. In this respect, with all the beneficial aspects of AquaCrop model, some adjustments should be added to it for soil and water salinity problems, especially in arid and semiarid regions. The study suggested that further research is needed using a crop simulation model to help optimize nitrogen and water management for silage maize.

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