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Water Supply

IWA PUBLISHING

Water Supply Vol 22 No 1, 602 doi: 10.2166/ws.2021.246

Evaluation of irrigation scheduling and yield response for wheat cultivars using the AquaCrop model in an arid climate

E. Amiri[a,*], A. Bahrani[b], S. Irmak[c] and N. Mohammadiyan Roshan[d]

[a] Department of Water Engineering, Lahijan Branch, Islamic Azad University, Lahijan, Iran
[b] Department of Agriculture, Ramhormoz Branch, Islamic Azad University, Ramhormoz, Iran
[c] Agricultural and Biological Engineering Department, The Pennsylvania State (Penn State) University, Pennsylvania, USA
[d] Department of Agronomy and Plant Breeding, Lahijan Branch, Islamic Azad University, Lahijan, Iran
*Corresponding author. E-mail: eamiri57@yahoo.com

EA, 0000-0002-5057-6759

ABSTRACT

Yield, soil water balance components and evapotranspiration-based water productivity (WP_{ET}) of three winter wheat cultivars were investigated using the AquaCrop model under arid conditions in Shiraz, Iran, for two consecutive years. The irrigation treatments were non-stressed (I_1) and post-anthesis water stress (I_2) with three wheat cultivars. Evaluation of the model was performed using the coefficient of root mean squared error (RMSE), normalized RMSE and R^2. The AquaCrop model performed well in simulating grain yield and final biomass production with $R^2 > 0.90$, and RMSE and normalized RMSE values less than 10. The I_1 treatment resulted in higher grain yield and biomass productivity than the I_2 treatment. The I_2 irrigation resulted in yield reduction of 21 and 24% in the 2006–2007 and 2007–2008 growing seasons, respectively, as compared with I_2. Using the measured grain yield and AquaCrop-simulated water balance, the amount of WP_{ET} was found to vary from 0.68 to 0.95 kg m^{-3}. The AquaCrop model was able to predict winter wheat biomass and yield production with a good accuracy in the arid conditions of this study and its ability to simulate these variables for different wheat cultivars' was especially notable. The AquaCrop model can be used to explore management scenarios to improve wheat water management in the study region.

Key words: AquaCrop model, water balance, water productivity, wheat

HIGHLIGHTS

- The AquaCrop model was calibrated and validated for wheat cultivars under irrigation management.
- During calibration and validation the model simulated biomass and yield well.
- Water balance and water productivity were calculated using the AquaCrop model.
- A range of evapotranspiration-based water productivity (WPET) from 0.68 to 0.95 kg m^{-3} is reported for arid areas of Iran.

INTRODUCTION

Wheat is the most widely grown cereal crop in the world and provides 20% of the daily protein and calories for nearly half of the world's population. After rice, it is the most important food crop in developing countries (GCARD 2012). Wheat is considered as a moderate water user crop, but in arid and semi-arid regions its water requirements can be substantial, requiring practice of effective water management strategies. On a global scale, water withdrawal for agricultural purposes accounts for about 75–80% of all water withdrawals and the Food and Agriculture Organization of the United Nations (FAO) has predicted a 14% net increase in water use to meet food demands by 2030 as compared with the year 2000 (FAO 2008). To meet this increasing demand for food by the world's rapidly growing population, effective irrigation management strategies need to be deployed to enhance the water productivity (WP) of major commodity crops.

In general, WP is computed as the ratio of grain yield to total water input, including irrigation and precipitation (WP_{I+R}) or to evapotranspiration (WP_{ET}). The WP_{ET} values for wheat found in previous studies showed a rather a wide variation, ranging from 0.6 kg m^{-3} to 1.7 kgm^{-3} (Zwart & Bastiaanssen 2004). Doorenbos & Kassam (1979) observed a narrower range of 0.8–1.0 kgm^{-3}. Irmak *et al.* (2015) measured grain yield, WP_{ET} and evapotranspiration (ET) rates for winter wheat through field experiments

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conducted in the 2008–2009 and 2009–2010 growing seasons in Nebraska, USA. Winter wheat grain yield averaged 4.55 tons/ha in both growing seasons. WP_{ET} was 0.76 $kg{\cdot}m^{-3}$ in 2008–2009 and 0.93 $kg{\cdot}m^{-3}$ in the 2009–2010 growing season. The seasonal ET was 600 and 490 mm during the 2008–2009 and 2009–2010 growing seasons, respectively. Akhtar (2017) analyzed ET from 2003 to 2013 for the Kabul River Basin, Afghanistan, using a surface energy balance system. The results of Akhtar (2017) show a mean ET of 215 $\pm$ 68 mm for the wheat growth period.

Measuring WP in real field conditions is a difficult, time consuming and costly task. Crop growth models can provide important and useful information and data in terms of how WP can change with environmental factors and management practices. The water-driven crop growth models usually assume a linear relation between biomass and transpiration through water productivity. This approach avoids the subdivision into different hierarchical levels, which results in a less complex modeling structure and reduces the number of input parameters (Steduto *et al.* 2009). The water-driven growth concept is used in the AquaCrop model (Raes *et al.* 2009; Steduto *et al.* 2009). The AquaCrop model needs less input parameters to simulate crop response to water use as compared with other simulation models (Amiri 2016; Zeleke 2019). The AquaCrop model has been calibrated, validated and used worldwide for optimization of irrigation management, deficit irrigation scheduling, yield response to water analyses, climate simulations and improvement of crop production (Abrha *et al.* 2012; Mebane *et al.* 2013). The model has been parameterized and tested for maize by using experimental data of six cropping seasons in California, USA (Hsiao *et al.* 2009). The AquaCrop model has also been used for simulating other crops' yields such as rice (Amiri 2016; Xu *et al.* 2019), soybean (Adeboye *et al.* 2017), cotton (Tsakmakis *et al.* 2018), maize (Rugimbana 2019; Sandhu & Irmak 2019a, 2019b), cereals (Mouchrif *et al.* 2019) and canola (Zeleke *et al.* 2011).

Zeleke & Nendel (2016) evaluated the AquaCrop model for two wheat cultivars (Gregory and Livingston) under rainfed and irrigated conditions in Australia. The root mean squared (RMSE) values between measured and simulated grain yield and above-ground biomass were 0.29 and 2.2 t ha^{-1}, respectively. Toumi *et al.* (2016) observed accurate water use and grain yield simulations after calibrating and validating the AquaCrop model for winter wheat under several irrigation management practices and planting dates. Mkhabela & Bullock (2012) found that the AquaCrop model simulates wheat yield with a coefficient of determination (R^2) of 0.66; the RMSE between measured and simulated yield was 89.9 kg ha^{-1}. Alizadeh *et al.* (2010) evaluated the AquaCrop model for simulating grain yield and for managing limited irrigation strategies for wheat, and showed that the model had sufficient accuracy to estimate wheat yield under full irrigation, limited irrigation and supplementary irrigation. In simulating wheat yield with the AquaCrop model in Iran, Khalili *et al.* (2014) demonstrated that the AquaCrop model has a potential for estimating crop yield with high accuracy. They reported R^2, normalized RMSE (RMSEn) and RMSE between the observed and simulated yield as 0.86, 0.062 kg ha^{-1} and 5.235 kg ha^{-1}, respectively. Kumar *et al.* (2014) reported that the AquaCrop model has acceptable accuracy in simulating grain yield of four wheat genotypes under four levels of irrigation water salinity levels in India and recommended that this model has acceptable accuracy in simulating wheat yields under such conditions. Teklu & Seleshi (2009) simulated the water productivity of maize under soil fertility scenarios (poor, near optimal and non-limiting) under rainfed conditions using the AquaCrop model in Africa. The result indicated that grain yield of maize increased from 2,500 kg ha^{-1} under poor to 6,400 kg ha^{-1} and 9,200 kg ha^{-1} with near optimal and non-limiting soil fertility conditions, respectively. Araya *et al.* (2010) evaluated the AquaCrop model for simulating biomass and yield of water deficient and irrigated barley in northern Ethiopia. They reported that the AquaCrop model performed well with model efficiency ranging from 0.50 to 0.95 for grain yield under various planting dates. Abedinpour *et al.* (2012) indicated that the AquaCrop model was more accurate in predicitng maize yield under full irrigation and 75% of field capacity (FC) management as compared with rainfed and 50% of FC. While the performance of the AquaCrop model has shown acceptable simulation performance, its performance evaluation of different wheat cultivars' response to different irrigation management practices under arid conditions is limited.

The objectives of this study were to: (i) evaluate the AquaCrop model performance in simulating different winter wheat cultivars' yields under two different irrigation levels (non-stressed and post-anthesis water stress) in arid conditions in Shiraz, Iran, and (ii) assess the capability of AquaCrop for simulation of soil water balance components and water productivity.

MATERIALS AND METHODS

Site description

The study was conducted at Shiraz Agricultural Research Station, Iran (29°50′N, 52°46′E) with an elevation of 1,810 m above mean sea level) during the two consecutive cropping seasons of 2006–2007 and 2007–2008. The study site, which is located about 15 km northwest of Shiraz, has a temperate climate with a mean annual rainfall of only 335 mm, and a mean annual air temperature of 18 °C.

Experimental details

In the field experiments, two levels of irrigation treatments, I_1 (non-stressed) and I_2 (post-anthesis water stress with irrigations managed at 65% of FC), were deployed as the main treatment (primary effect) and three wheat cultivars, Marvdasht (C_1), Chamran (C_2) and Shiraz (C_3), were used as sub-treatments (secondary effect). The experiment design was a split plot with a randomized block design with four replications of each treatment (Figure 1).

Soil samples were used to determine physical and chemical soil properties (Table 1). According to recommendations of the Soil Testing Laboratory of Shiraz Agricultural Research Station, nitrogen, phosphorus and potassium (N, P and K) fertilizers were applied in the form of urea, superphosphates and potassium sulfate, respectively. Wheat was sown on 11 and 14 November in the 2006–2007 and 2007–2008 wheat growing seasons, respectively, using a cone-seeder. Each experimental plot was 8 m long and 1.5 m wide and consisted of 6 wheat rows with a 0.20 m row spacing. Plots were plowed and disked after winter wheat harvest in July of the 2006–2007 growing season. The plots were disked again before seeding in November. Irrigation amounts of each main plot were determined via field-calibrated gypsum block soil moisture sensors. Six gypsum blocks were installed in each replicated plot at a soil depth of 30 cm. The irrigation system was operated in such a way that surface run-off did not occur. The four middle rows (of six-row experimental plots) in each replication were harvested for grain yield data, avoiding any potential edge effect.

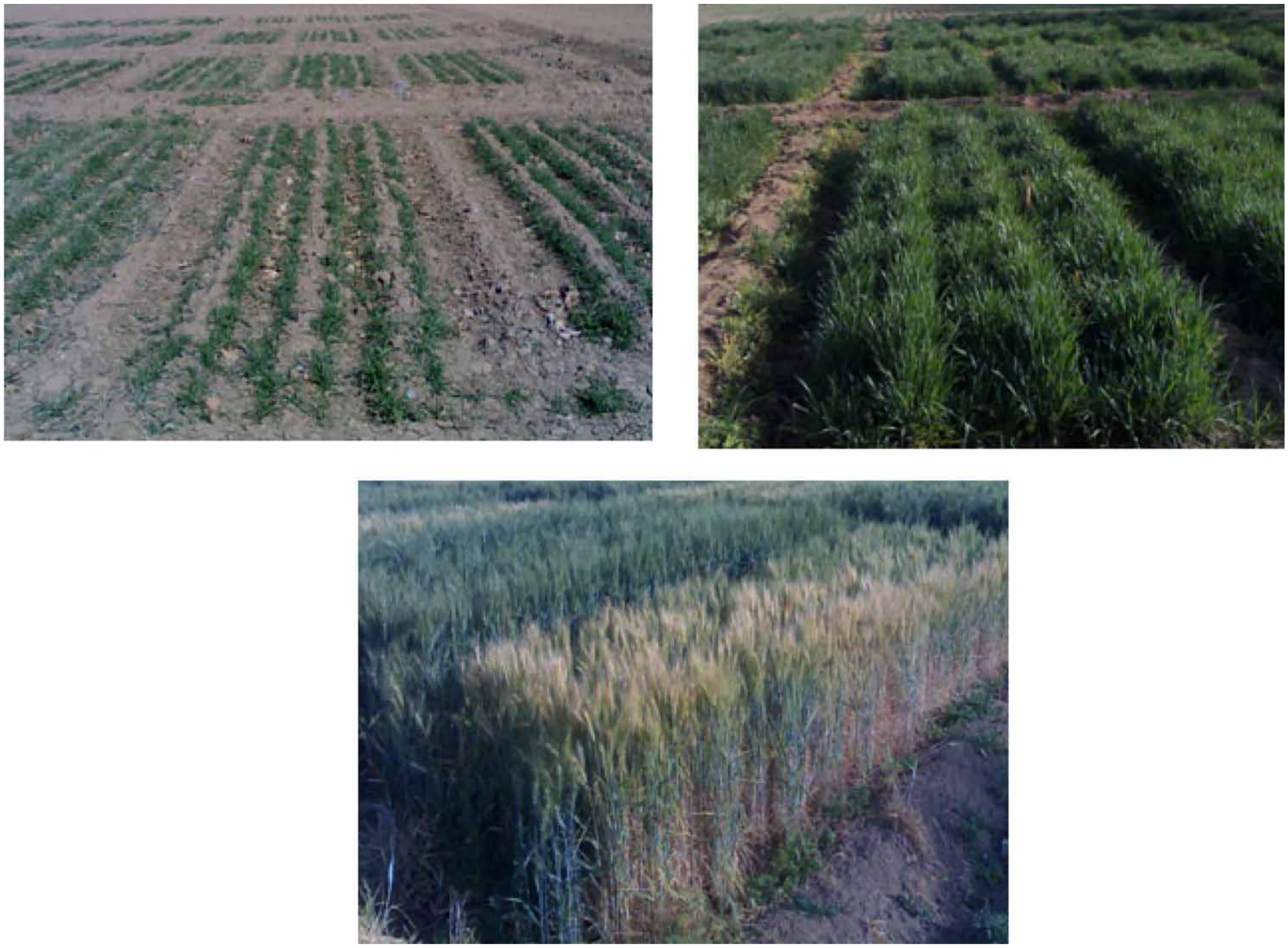

Figure 1 | Overview of the crop season.

Table 1 | Physical and chemical characteristics of the soil in the experimental field

Variable	2006–2007	2007–2008
Texture	Silty clay	Silty clay
θ_{sat} (%)	45	45
FC (%)	25	25
WP (%)	14	14
K_{sat} (mm d^{-1})	100	100
pH	7.96	7.85
EC (dS m^{-1})	1.88	1.25
Organic matter (%)	0.25	0.39
N (%)	0.023	0.036
P (mg Kg^{-1})	5.4	16
K (mg Kg^{-1})	340	206
Fe	3.7	5.4
Zn	0.64	0.1
Mn	5.8	9.9
Cu	0.48	0.98

AquaCrop model

AquaCrop is a crop growth model that was developed by the Land and Water Division of the FAO for simulation of crop yields of the major herbaceous crops in response to water and climate (Steduto *et al.* 2009). The AquaCrop model's soil-plant-atmosphere continuum module includes a soil water balance, crop development and growth and yield, atmosphere thermal regime, rainfall, evaporative demand and CO_2 concentration processes. Some management aspects, which also affect the soil water balance, crop development and final yield, are considered in the model. In this model, the effects of pests, diseases and weeds are not considered (Raes *et al.* 2009) and it is assumed that crops are grown under optimal conditions in terms of disease stress and nitrogen amount.

In this study, the AquaCrop model version 6.1 was calibrated and validated for winter wheat using two wheat growing seasons of field experimental data (2006–2007 season for calibration and 2007–2008 for validation) to evaluate the model performance in terms of simulation of yield and biomass, in response to different water management strategies.

Model inputs

The AquaCrop model requires a small number of input variables as compared with other crop models. The model is intended to follow an optimum balance between accuracy, simplicity and robustness. The yield of product separation to biomass and harvest index enables the effect of environment on biomass and harvest index to be determined. By using the separation of the effect of the environment on biomass and the harvest index can aid in identifying the adverse effects of water stress on them. The model enables partitioning of crop ET into transpiration and evaporation components. Partitioning ET into transpiration and evaporation prevents non-productive use of water through evaporation, especially during partial canopy closure in the early growing season. Daily transpiration (Tr_i) is normalized using daily grass reference evapotranspiration (ET_o) and WP (Raes *et al.* 2009; Steduto *et al.* 2009).

Model evaluation

First, sensitivity analysis of the AquaCrop input parameters was performed using a sensitivity coefficient relationship (Equation (1)) and the parameters that have most influence on the results derived from model simulations (output data) was found.

$$S_c = \frac{\Delta W/\bar{W}}{\Delta P/\bar{P}} \tag{1}$$

In Equation (1): S_c: dimensionless sensitivity factor; ΔW: difference between the amount of output parameters before and after the change of input parameters; $\bar{W}$ average output parameter before and after changing of input parameters; ΔP difference between input parameter amounts; and $\bar{P}$ is the average amount of input of one parameter in the model. The sensitivity coefficient variation range suggested by Heng *et al.* (2009) was used with Equation (1) for the sensitivity analysis (Table 2). To performance sensitivity analysis, at each turn of running the AquaCrop model, one of the input parameters was changed to ±25 percent, and other parameters were kept constant and the model was run using the new conditions. After doing sensitivity analysis and preparation of model input data in the form of meteorological data, precipitation, ET, irrigation, soil and plant data files, the model was calibrated by using the biomass and yield measured data for 2006 and model validation was conducted using 2007 data. By changing the calibration coefficients of the model and based on the best match between output results and measured data, the calibration coefficients were obtained by trial and error.

In order to evaluate the model performance, several statistical indices were used to compare the simulated and observed values. In addition to R^2, RMSE and $RMSE_n$ indices were used for evaluation (Equations (2) and (3) respectively). These statistical indices are effective and commonly used to test the fitness of models (Bouman & van Laar 2006):

$$\mathrm{RMSE} = \left(\sum_{I=1}^{n} (P_i - O_i)^2 / n \right)^{0.5} \tag{2}$$

$$\mathrm{RMSE_n} = 100 \left(\sum_{I=1}^{n} (P_i - O_i)^2 / n \right)^{0.5} / O_{mean} \tag{3}$$

In these equations, P_i is the predicted value, O_i is the observed value, O_{mean} is mean observed value, and n is the number of observations. The goodness of fit and statistical significance between the observed and estimated values were assessed by using paired t-test (at the 5% significance level) and linear regression analysis.

Soil water balance

Soil water balance in the model includes the processes of surface run-off, evaporation, transpiration, internal or redistribution drainage, deep percolation, infiltration, capillary rise and crop water uptake. Incoming and outgoing water fluxes at the crop root zone boundaries and water retained in the root zone are determined on a daily time step using a soil water balance module (Steduto *et al.* 2009). A specific and important trait of the soil water balance in the model is the separation of evaporation from transpiration based on the modified Ritchie approach (Ritchie 1972). The separate estimates of evaporation and transpiration can be beneficial for different applications, including developing transpiration-based water productivity values and estimation of water losses through soil evaporation in different cropping systems under different management practices. This partitioning is especially important in water-limiting regions. Transpiration is correlated with canopy cover, which is proportional to the degree of soil cover, and evaporation is proportional to the area of soil that is not covered by vegetation (Steduto *et al.* 2009).

Water productivity

Crop water productivity is described as the crop (grain yield and/or biomass) production per unit of water used (Molden 1997; Molden *et al.* 2001; Irmak 2015a) and can be an important variable to evaluate a cropping system's response to water under different management practices (Irmak 2015a, 2015b). Kassam & Smith (2001) defined the productivity of water as a unit of crop yield production per unit of water consumed in ET. Considering different types of plant parts that may be considered as production (fresh biomass, dry matter or grain yield) and water used (transpiration, ET, precipitation, deep percolation and irrigation), water productivity can be described in different ways (Molden *et al.* 2001) (Table 3), depending on the objectives.

Table 2 | Proposed classification for sensitivity coefficient variation range (Heng *et al.* 2009)

Variation range	$S_c = 0$	$0 < S_c < 0.3$	$0.3 < S_c < 1.5$	$S_c > 1.5$
Severity of sensitivity	No sensitivity	Low sensitivity	Moderate sensitivity	High sensitivity

Table 3 | Water productivity (kg m^{-3}) defined as observed grain yield (kg m^{-2}) per unit of water (m^3 m^{-2})

WP	Definition	Unit	Field scale
WP_T	Yg/T	kg m^{-3}	T
WP_{ET}	Yg/ET	kg m^{-3}	E + T
WP_I	Yg/I	kg m^{-3}	I
WP_{I+P}	Yg/(I + P)	kg m^{-3}	I + P

RESULTS AND DISCUSSION

Model evaluation

The results of sensitivity analysis for a number of input parameters for the AquaCrop model are presented in Table 4. Based on the variation range proposed by Heng *et al.* (2009) results showed that the model has very little sensitivity towards canopy decline coefficient, initial canopy cover, germination time, sowing time to maximum root growth, physiological maturity time, lower and upper threshold for canopy expansion and upper threshold for stomatal closure, and shape factor describing root zone expansion. So the measurement error of those data at farm level is negligible. Also, the AquaCrop model's sensitivity to changes in maximum canopy cover, crop coefficients (Kc), crop water productivity, harvest index and time of sowing to maximum canopy cover is more than other parameters.

For calibration of the model, the experimental data of the 2006–2007 growing season were used and the data from the 2007–2008 growing season were used for validation. The growth parameters used in AquaCrop for the three wheat cultivars are presented in Table 5. The model was evaluated based on the simulation of grain yield and biomass for two irrigation regimes. The calibrated parameters were used for validation and evaluation of the model. The statistical indices used for evaluation of the model performance are shown in Table 6. In comparison between the observed (varied between 3,611 and 6,200 kg ha^{-1}) and simulated grain yield (varied between 3,922 and 6,166 kg ha^{-1}), RMSE ranged from 99 to 368 kg ha^{-1} and normalized RMSE was between 1.99 to 7.67%, which are considered to be acceptable. For biomass production, RMSE was between 788 and 1,476 kg $ha^{-1}$and normalized RMSE ranged from 4.68 to 8.99%. The observed biomass production varied between 14,200 and 19,400 kg ha^{-1} and simulated biomass ranged from 14,358 to 19,142 kg ha^{-1}. The statistical

Table 4 | Sensitivity coefficient of some input parameters of the AquaCrop model

Input parameters	S_c value in ±25%	Severity of sensitivity
Emergence time	0.01–0.02	Low sensitivity
Time from sowing to maximum rooting growth	0.018–0.03	Low sensitivity
Time from sowing to maximum canopy cover	0.51–0.54	Moderate sensitivity
Maturity time	0.07–0.09	Low sensitivity
Maximum canopy cover (%)	0.62–0.68	Moderate sensitivity
Canopy decline coefficient (%/day)	0.18–0.22	Low sensitivity
Crop water productivity (g m^{-2})	0.79–0.86	Moderate sensitivity
CC_0 (%)	0.01–0.013	Low sensitivity
Kc	0.48–0.52	Moderate sensitivity
Reference harvest index (%)	0.99–1.00	Moderate sensitivity
Shape factor describing root zone expansion	0.01–0.02	Low sensitivity
Upper threshold for canopy expansion	0.01–0.02	Low sensitivity
Lower threshold for canopy expansion	0.11–0.18	Low sensitivity
Upper threshold for stomata closure	0.10–0.14	Low sensitivity
Upper threshold for canopy senescence	0.00	No sensitivity

Table 5 | Input data of wheat cultivar parameters used in the AquaCrop model

Description	Chamran	Marvdasht	Shiraz	Unit
Base temperature	0	0	0	°C
Cut-off temperature	26	26	26	°C
Canopy growth coefficient (CGC)	4.75	4.62	5.24	% day^{-1}
Canopy decline coefficient (CDC) at senescence	8.00	6.77	7.18	% day^{-1}
Maximum canopy cover (CCx)	0.92	0.87	0.96	%
Normalized water productivity (WP)	15	15	15	g m^{-2}
Reference harvest index (HIo)	38	35	43	%
Time from sowing to emergence	9	9	9	days
Time from sowing to start flowering	170	167	130	days
Time from sowing to start senescence	185	180	150	days
Time from sowing to maturity	214	217	175	days
Length of the flowering stage	15	15	15	days

Table 6 | Evaluation results of AquaCrop simulations of grain yield (kg ha^{-1}) and biomass (kg ha^{-1}) for calibration and validation datasets

Growing season	Crop variable	X_{obs}(SD)	X_{sim}(SD)	RMSE	$RMSE_n$	α	β	R^2	t-test
2006–2007	Yield	4,974(862)	4,996(806)	99	1.99	0.93	359	0.99	0.48
	Biomass	16,839(1,832)	17,309(1,393)	788	4.68	0.75	4,602	0.98	0.31
2007–2008	Yield	4,802(1,000)	4,900(809)	368	7.67	0.78	1,160	0.93	0.43
	Biomass	16,417(1,576)	15,506(784)	1,476	8.99	0.47	7,738	0.90	0.12

X_{obs}, mean of measured values in whole population; X_{sim}, mean of simulated values in whole population; SD, standard deviation of population; α, slope of linear relation between simulated and measured values; β, intercept of linear relation between simulated and measured values; R^2, adjusted linear correlation coefficient between simulated and measured values; RMSE, absolute root mean squared error; $RMSE_n$, normalized root mean squared error.

indicators (RMSE and $RMSE_n$) all showed a better performance for yield than biomass. The values obtained for the wheat cultivars were the closest to those found by Rosa *et al.* (2020) (RMSE = 398–508 kg ha^{-1}), which validated AquaCrop for the wheat crop considering the parameters suggested by Raes *et al.* (2009). Akumaga *et al.* (2017) differentiated between observed and AquaCrop model-simulated yield values between −30 to +19% and RMSE of simulated grain yield between 8 and 17% for calibration and validation data. Araya *et al.* (2010) simulated the highest deviation for final biomass, at 8.5%. Vahdati *et al.* (2020) reported in their simulation of rice biomass and grain yields that the relative error percentages of the model for them were in the −38% to 20% and −22% to −11% ranges, respectively.

Paired t-test results showed that there was no significant ($p > 0.05$) difference between the observed and simulated grain yield or biomass values (Table 6). The relationships between simulated versus observed grain yield and biomass production are presented in Figure 2. Results showed that the AquaCrop model estimated grain yield with an acceptable precision. The slope of regression line, α, for grain yield was close to 1 and intercept value, β, was relatively small. Furthermore, the R^2 value of the linear regression model was larger than 0.90, indicating strong correlation. On the other hand, the slope of regression line for biomass differed from 1, especially in the second growing season, and the intercept value was relatively large even though the R^2 value was greater than 0.90. Andarzian *et al.* (2011) reported $R^2 > 0.95$ when simulating different wheat cultivars' yields, under both full and deficit irrigation conditions using AquaCrop.

The model overestimated biomass in the 2006–2007 growing season and underestimated it in 2007–2008. Seasonal rainfall was 336 mm in 2006–2007 and it was much lower (119 mm) in 2007–2008. A difference of 217 mm rainfall can significantly impact crop growth and development and may cause crop water stress and cause yield reduction, especially in arid conditions, which may not be effectively accounted for by the model and can cause differences in model performance between years. Since the model simulations and performance are sensitive to soil moisture and other water components,

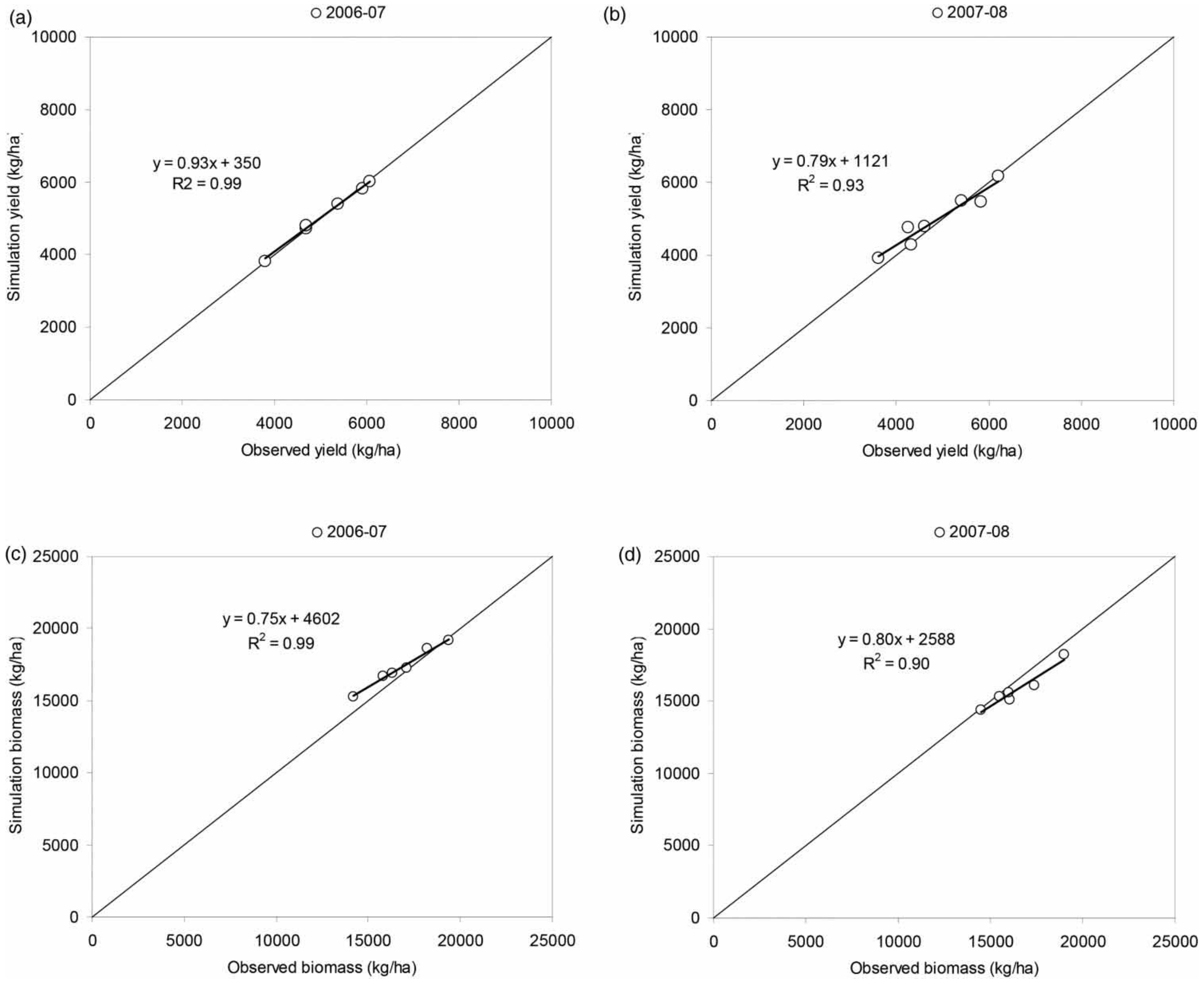

Figure 2 | Simulated versus observed (a) grain yield, first year, (b) grain yield, second year, (c) biomass, first year and (d) biomass, second year.

the differences in soil-water dynamics between the two growing seasons could be one of the reasons for differences in performance of the model in simulating biomass production differently between the years.

Figure 3 illustrates the performance of the model in simulating wheat yield and biomass for two different water management strategies. Changing irrigation management from a non-stressed (full irrigation) to water-stressed strategy leads to yield decrease, and the decrease in yield varied with the wheat cultivars' characteristics. The Chamran cultivar had the maximum decrease in yield under water stress conditions, which was about 24%. The model also simulated the grain and biomass yield in water-stressed conditions with poor to moderate accuracy as compared with non-stressed conditions in both validation and calibration phases for all cultivars. Under water stress, the measured grain yield was reduced by 21% and the model-simulation results showed a similar trend of yield decrease at 18%.

As shown in Table 6, the effect of irrigation treatments on the grain yield and biomass for both observed and simulated data were statistically significant ($p < 0.05$). The standard deviation, RMSE and $\mathrm{RMSE_n}$ also showed that post-anthesis water stress resulted in a significant decrease in yield and biomass. The I_1 treatment resulted in higher yield and biomass than I_2 with post-anthesis water stress (Figure 3 and Table 7). In general, observed grain yield and biomass in the 2006–2007 growing season were slightly higher than in the 2007–2008 season because of differences in seasonal rainfall (Table 8). Based on the

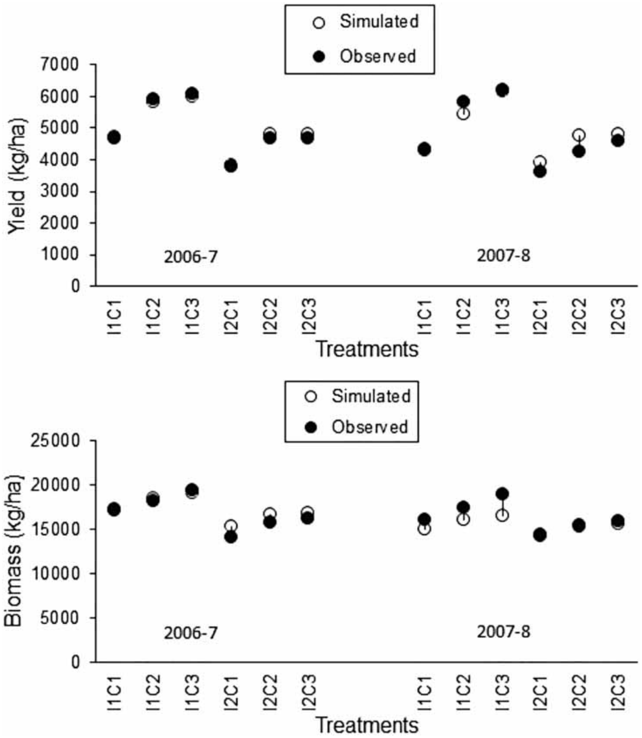

Figure 3 | Simulated and observed wheat yield and biomass under two different irrigation regimes for 2006–7 and 2007–8 growing seasons. Vertical bars display the standard deviation. I: Irrigation, C: Cultivar.

Table 7 | Statistical indices to assess the effect of irrigation treatments on grain yield (kg ha^{-1}) and biomass (kg ha^{-1}) for both observed and simulated data

Data type	Crop variable	X_{I1}(SD)	X_{I2}(SD)	RMSE	$RMSE_n$	t-test
Observed	Yield	5,503(791)	4,272(474)	1,561	28.4	0.004
	Biomass	17,861(1,248)	15,394(858)	3,101	17.4	0.001
Simulated	Yield	5,411(753)	4,485(478)	1,203	22.2	0.01
	Biomass	17,129(1,541)	15,687(941)	1,931	11.3	0.04

Table 8 | Water balance components under two different irrigation regimes and three cultivars of winter wheat

		Soil water balance components (mm)^{a}						
Growing season	Treatment	I	P	T	E	ET	D	ΔS
2006–2007	I1C1	710	336	487	156	643	431	−28
	I1C2	710	336	519	122	641	429	−24
	I1C3	710	336	542	118	660	342	44
	I2C1	510	336	399	150	549	394	−97
	I2C2	510	336	435	120	555	387	−96
	I2C3	510	336	443	116	559	386	−99
2007–2008	I1C1	655	119	458	177	635	143	−4
	I1C2	655	119	483	141	624	141	9
	I1C3	655	119	507	143	650	140	−16
	I2C1	510	119	424	151	575	143	−89
	I2C2	510	119	449	120	569	141	−81
	I2C3	510	119	458	128	586	140	−97

[a] All values were estimated by model except I (Irrigation) and P (Precipitation).

I, Irrigation; P, Precipitation; T, Transpiration; E, Evaporation; ET, Evapotranspiration; D, Deep percolation; ΔS, Soil moisture storage.

model-simulated results, in comparison to I_1, the I_2 strategy resulted in higher yield reduction by 21 and 24% in the 2006–2007 and 2007–2008 growing seasons, respectively.

The inaccuracy in yield and biomass simulation by AquaCrop under water stress conditions points towards the model's less adequate algorithms for duration of water stress (Heng *et al.* 2009) in certain conditions. The results of this study indicate that the AquaCrop model performance declines under water stress, especially in temperate conditions where the timing and magnitude of water stress may not be simulated accurately. Thus, further adjustment of water stress thresholds in the model may improve the simulations considerably under water stress. Water stress can have substantial influence on crop growth and development, thus the relationships between water stress and crop growth parameters should be further investigated in temperate climates. Furthermore, the appropriate calibration of crop growth stages, canopy growth coefficient (CGC), canopy decline coefficient (CDC) and normalized water productivity (WP) under different water stress conditions can further improve the model's performance in simulating yield and biomass production in arid regions (Sandhu & Irmak 2019b).

Water balance components

Table 8 presents the water balance components determined through field experiments. The amounts of irrigation applied in the I_1 treatment were 710 and 655 mm in 2006–2007 and 2007–2008 seasons, respectively. The irrigation amount in the I_2 treatment was 510 mm for both growing seasons. The amount of deep percolation varied between 342 and 431 mm in the first growing season and between 140 and 143 mm in the second growing season. For the two growing seasons, the simulated ET ranged from 549 to 660 mm. In non-irrigated semi-arid areas, the amount of ET as well as evaporation can be lower under water-limiting conditions. However, under well-irrigated conditions, ET can reach 600–800 mm in arid regions of Iran. The reduction in irrigation depth could decrease the soil water content, further decreasing the hydraulic conductivity and thereby decreasing the evaporation rate (Hillel, 1971). Steduto *et al.* (2012) reported that the total cumulative ET of wheat ranged from 200 to 500 mm. Jalil *et al.* (2020) also reported a range of ET from 348 to 385 mm under arid areas of Afghanistan. Ghaderi *et al.* (2020) reported the greatest and least amount of water required were 231 and 19.47 mm/hr, respectively.

The amounts of evaporation, transpiration and ET for the I_2 treatment were also reduced by 3, 18 and 14%, respectively, in the 2006–2007 growing season and by 13, 8 and 9%, respectively, in the 2007–2008 growing season. Depending on treatments and sub-treatments, the evaporation rate varied from 116 to 156 mm in 2006–2007 and from 120 to 177 mm in the 2007–2008 growing season. Because of post-anthesis water stress, the amount of evaporation for the I_2 treatment was less than I_1 for both seasons. The transpiration rate ranged from 399 to 542 mm in 2006–2007 and from 424 to 507 mm in the 2007–2008 growing season with the I_2 treatment having 65 mm less transpiration than I_1 due to post-anthesis water stress imposed in the I_2 treatment. Zhao *et al.* (2020) mentioned a range of transpiration from 328 mm up to a maximum of 442 mm for wheat under rainfed, limited and sufficient-irrigation treatments.

Water productivity

Table 9 shows the amount of water productivity for all treatments and sub-treatments. Water productivity values were calculated using simulated transpiration and ET and the observed grain yield. The amount of WP_{ET} varied from 0.68 to

Table 9 | Yield and water productivity of winter wheat (kg m^{-3}) under different treatments

Growing season	Treatment	WP_T	WP_{ET}	WP_I	WP_{I+P}
2006–2007	I1C1	0.96	0.73	0.66	0.45
	I1C2	1.14	0.92	0.83	0.57
	I1C3	1.12	0.92	0.85	0.58
	I2C1	0.95	0.69	0.74	0.45
	I2C2	1.08	0.84	0.92	0.55
	I2C3	1.06	0.84	0.92	0.55
2007–2008	I1C1	0.94	0.68	0.66	0.56
	I1C2	1.21	0.93	0.89	0.75
	I1C3	1.22	0.95	0.95	0.80
	I2C1	0.85	0.63	0.71	0.57
	I2C2	0.95	0.75	0.83	0.68
	I2C3	1.01	0.79	0.90	0.73

0.95 kg m^{-3}. The amount of WP_T varied from 0.85 to 1.22 kg m^{-3}. In general, the low values of WP_{ET} and WP_T were obtained in the I_2 treatment for the Marvdasht cultivar. High WP_{ET} was also accompanied with high yield for both growing seasons. These results are in general agreement with those reported in the literature. Steduto *et al.* (2012) obtained a WP_T range of 1.0–1.20 kg m^{-3}. Zwart & Bastiaanssen (2004) reported a WP_{ET} range from 0.6 to 1.7 kg m^{-3}. Zhao *et al.* (2020) also mentioned a range of WP_{ET} from 0.52 kg m^{-3} up to a maximum of 1.72 kg m^{-3} for wheat. Andarzian *et al.* (2011) also reported a range of WP_{ET} from 1.35 to 1.45 kg m^{-3}. Xu *et al.* (2016) mentioned that WP_{ET}, which was calculated based on observed grain yield and ET, increased as the cumulative irrigation increased.

Table 8 also showed that WP_{ET} decreased by 16 to 39% as compared with WP_T. The amount of WP_I varied from 0.66 to 0.95 kg m^{-3}. The amount of WP_{I+P} varied from 0.45 to 0.80 kg m^{-3}, which is lower than the values reported in the literature. Zhao *et al.* (2020) reported a range of WP_I from 0.78 to 2.29 kgm^{-3} for wheat. Xu *et al.* (2016) showed that maximum WPs were obtained when wheat was irrigated at the heading and post anthesis stages.

CONCLUSIONS

The water-driven AquaCrop growth model was used to simulate grain and biomass production and water balance parameters such as ET, and transpiration for three wheat cultivars, and some of these variables were compared to field-measured values observed under two different irrigation management strategies to evaluate the estimation performance of the model in a temperate region. The model estimated grain yield and biomass with an acceptable precision and there was no significant difference between the observed and simulated grain yield or biomass production ($R^2 > 0.90$; and $RMSE_n$ values <10). Using the measured grain yield and simulated water balance, the average amounts of WP_I, WP_{I+P}, WP_{ET}, and WP_T based on grain yield were quantified as 0.6, 0.82, 0.81 and 1.04 kg m^{-3}, respectively. This model can be recommended for estimating growth and development variables of winter wheat cultivars studied under these study conditions. The model's performance, especially in adequately simulating different wheat cultivars' yield and productivity, is a very important and positive notable feature of the model.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGEMENTS

The authors wish to thank the Ramhormoz Branch, Islamic Azad University, for its support during the research.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 31 January 2021; accepted in revised form 19 July 2021. Available online 5 August 2021