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Assessment of DSSAT and AquaCrop models to simulate soybean and maize yield under water stress conditions

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Abstract

Aim of study: To evaluate the performance of DSSAT and AquaCrop models in the estimation of soybean and grain maize yield under water stress conditions in a semi-arid region.

Area of study: Kermanshah, Iran.

Material and methods: AquaCrop and DSSAT were assessed to simulate soybean and maize. Both models were calibrated using field data. Field experiments were performed in a randomized complete block design with eight and four irrigation treatments for soybeans and maize, respectively with three replications. Measures of Normalized Root Mean Square Error (nRMSE) and Nash-Sutcliffe Model Efficiency were used to evaluate the accuracy of the models. For this purpose, simulated values of leaf area index / green crop canopy, grain yield, biomass, and soil moisture were compared with measured data.

Main results: Results indicated that the CROPGRO-Soybean in DSSAT software simulated more accurate crop growth of soybean than AquaCrop. The average nRMSE of the DSSAT model for estimating soil moisture, leaf area index, grain yield, and biomass were 6%, 14%, 16% and 20%, respectively. For maize, AquaCrop simulated crop growth more reliably than CERES-maize. The average nRMSE of 3%, 10%, 13% and 27% of the Aquacrop model in simulating the parameters of soil moisture, green crop canopy, biomass, and grain yield.

Research highlights: Considering the better performance of AquaCrop for maize and DSSAT for soybean in the study area, it is not possible to propose a specific model to simulate the growth of all crops in a region.

Additional key words: CERES-Maize; CROPGRO-Soybean; crop growth models; crop yield; Kermanshah; soil moisture.

Abbreviation used: DSSAT (Decision Support System for Agrotechnology Transfer); DW (dry weight); EF (Nash-Sutcliffe Model Efficiency); ETa (actual crop evapotranspiration); ETc (potential crop evapotranspiration); ETo (reference crop evapotranspiration); HI (harvest index); LAI (leaf area index); nRMSE (normalized root mean square error).

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Introduction

Water is one of the most important crop growth requirements, which is limited in many parts of the world. In conditions of water scarcity, crop water use efficiency must be increased to increase food production. Deficit irrigation is one of the irrigation management methods, especially in the situation of water scarcity, which is also associated with the reduction of crop yield. The incidence of water stress at any stage of crop growth can decrease crop yield, but the severity and magnitude of yield loss depend on the time and severity of the water stress (Brevedan & Egli, 2003). Therefore, it is necessary to study crop yield and water requirements under water stress conditions. These can be studied through field experiments. Since investigating the effects of limiting factors (such as water) on crop growth requires many expensive experiments in different regions, providing a solution to reduce the number of these tests is very important. With advances in modeling science, several crop growth simulation models (e.g., WOFOST, DSSAT, CropSyst, AquaCrop, …) have been developed. Considering the variety of existing models, choosing the most appropriate crop growth simulation model for each crop in each region is essential. Evaluation of irrigation management, especially in water scarcity conditions, is one of the issues that have been studied using crop growth simulation models. Since in this study, the CERES-Maize (Jones & Kiniry, 1986) and CROPGRO (Boote et al., 2018) models in the DSSAT software package (Jones et al., 2003) and the AquaCrop (Raes et al., 2009) have been used, the literature review has been limited to these models.

Decision Support System for Agrotechnology Transfer (DSSAT) is a software package, which was developed as the result of an international effort to facilitate the use of models in agricultural research. Crop growth simulation models such as CERES-Maize, CERES-Wheat, and CROPGRO are at the center of this collection (Jones et al., 2003). DSSAT has been used worldwide for different purposes (e.g., determination of optimum crop management practices, irrigation management, precision agriculture, the impact of climate change on crop yield, etc.) at different spatial and temporal scales (Soltani & Hoogenboom, 2007). Many studies have shown that the CERES-Maize model can reliably simulate phenological development, biomass accumulation, crop yield, nitrate leaching, and nitrogen uptake (Abedinpour & Sarangi, 2018; Malik et al., 2019). Abedinpour & Sarangi (2018) assessed the CERES-Maize model in estimating maize yield using different levels of water and nitrogen. Their results showed that although this model simulated corn yield with acceptable accuracy, it was less accurate in higher water stress treatments. Hammad et al. (2018) studied the accuracy of CERES-Maize in Faisalabad, Pakistan, and concluded that this model accurately simulated phenological development, grain yield, and final biomass production of maize under various water regimes and nitrogen rates.

The acceptable accuracy of the CROPGRO-Soybean model in the simulation of soybean phenological stages and yield has been confirmed in various studies (Kumar et al., 2008; Ovando et al., 2018; Teixeira et al., 2019). CROPGRO-Soybean also was used to assess the impacts of water stress on soybean yield. Sharda et al. (2019), after calibration and validation of CROPGRO-Soybean in their study area, have used the calibrated model to investigate the effect of irrigation depth on crop yield and water productivity. Although several studies show satisfactory results of CROPGRO-Soybean under water stress conditions, examples of model inefficiencies in these conditions have also been reported (Dogan et al., 2007).

AquaCrop is a crop-water productivity model to simulate yield response to water developed by FAO (Food and Agriculture Organization of the United Nations). Concepts and basic principles of the AquaCrop model were described by Steduto et al. (2009), and its main algorithms and software description were presented by Raes et al. (2009). This model is derived from the equation of Doorenbos & Kassam (1979). The ease of use of the AquaCrop model due to the need for low input parameters and sufficient simulation accuracy has made this model a valuable tool for simulating crop growth under different irrigation scenarios (Heng et al., 2009). AquaCrop was developed in 2009 and since then it has been used worldwide in different agro-ecological conditions to simulate the yield response of various crops to water such as wheat (Andarzian et al., 2011; Mkhabela & Bullock, 2012), barley (Hellal et al., 2019), cotton (García-Vila et al., 2009), sugar beet (Malik et al., 2017), saffron (Mirsafi et al., 2016) and many other crops (Araya et al., 2010). This model is also used for the simulation of soybean and maize. The use of AquaCrop in the simulation of maize growth and yield in Uganda (Mibulo & Kiggundu, 2018) and maize responses to different nitrogen stresses under the semi-arid climate in Iran (Ranjbar et al., 2019) have also been reported. Paredes et al. (2015) used the AquaCrop model to simulate soybean growth in North China. Based on the results, they claimed that the model would predict yield and biomass well if adequately parameterized. Adeboye et al. (2019), based on their study, concluded that the AquaCrop model is adequate in simulating canopy cover, dry above-ground biomass, and grain yield of rainfed soybean in Ile-Ife, Nigeria. Heng et al. (2009) used the AquaCrop model to simulate maize growth in three regions with different conditions (Spain, Texas, and Florida). Their results showed that the AquaCrop model could satisfactorily simulate crop water consumption under high evapotranspiration and wind speed. Although the accuracy of this model has been reported to be adequate in many cases, there are examples of inadequate accuracy of this model in the literature, especially in moderate to severe water stress conditions. Sandhu & Irmak (2019) used the AquaCrop model to simulate maize evapotranspiration, growth, yield, and also water use efficiency, on different planting dates under irrigated, and rainfed conditions in Nebraska, USA. Based on their results, the accuracy of the model was lower under arid climate conditions; the model overestimated crop yield and underestimated potential evapotranspiration; as a result, water use efficiency was overestimated. Ahmadi et al. (2015) reported that the accuracy of AquaCrop is insufficient to simulate maize yield under moderate to severe water stress conditions.

The performance of crop growth simulation models was compared in several studies. Battisti et al. (2017) assessed the accuracy of five crop growth simulation models (including AquaCrop and DSSAT) in the simulation of soybean. Their results showed that most of the models still have difficulties in simulating soybean yield accurately under severe water deficit conditions. Babel et al. (2019) evaluated the performance of AquaCrop and DSSAT-CERES for maize in the higher Himalayan region of India. Although their results showed that both models were suitable, they recommended the AquaCrop model because of its low data requirement. Castañeda-Vera et al. (2015) assessed the usefulness of Aquacrop, CERES-Wheat, CropSyst, and WOFOST in wheat simulation. They concluded that CERES-Wheat and CropSyst are preferable for growing wheat in semi-arid conditions.

In this study, the crops of soybean (*Glycine max* L.) and grain maize (*Zea mays* L.) were studied. According to the statistics published on the Information and Communication Technology Center website of the Iranian Ministry of Agriculture Jahad (2016-2022), corn and soybeans rank first to third among Iran's agricultural products (https://amar.maj.ir/page-amar/FA/65/form/pId28832). More than 90% of edible oil consumed is imported into Iran. Soybean, which is one of the primary sources of high-quality oil and protein, is commonly used in human food consumption (Sinclair et al., 1991). Maize is one of the most widely used agricultural products in Iran. Its production does not meet the domestic demand. Maize is a lucrative and favorite crop for farmers in the study area, which of course has high crop water consumption. Due to the water shortage in recent years, the area underplanting of maize has decreased. In some areas of Kermanshah province, farmers have been directed to plant soybean instead of maize. Although AquaCrop and DSSAT models have been used in different parts of the world to estimate the yield of corn and soybean under water stress, the performance of these models has not been evaluated in the studied area. This study aimed to evaluate the performance of a specific model (packages of CERES-Maize and CROPGRO-Soybean in DSSAT) and a generic model (AquaCrop) in the estimation of soybean and grain maize yield under water stress conditions in a semi-arid region in the west of Iran.

Material and methods

Crop growth simulation models

Crop growth simulation models differ in terms of data requirements, the type of plants that can be simulated, and the level of complexity. Some models are developed to simulate a specific crop, while others can be used for a variety of crops. In this study, a specific model (DSSAT) and a generic model (AquaCrop) were used to simulate the growth of soybean and maize under water-limited conditions. Although these models have been successfully used in different parts of the world to study the crop yield response to water stress (Adeboye et al., 2017; Malik et al., 2017; Babel et al., 2019; Hellal et al., 2019; Sandhu & Irmak, 2019), they have not yet been investigated in the study area. The basic principles and manual of these models are available on the website of these software developers as well as in the literature (Jones et al., 2003; Steduto et al., 2009; Hoogenboom et al., 2019). Therefore, in this article, only a brief explanation of these models has been given.

AquaCrop model

AquaCrop is a crop growth simulation model which simulates crop biomass and harvest regarding water availability (Steduto et al., 2009). The basic equation of this model is based on Doorenbos & Kassam's (1979) approach in the FAO 33 report (Eq. 1).

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y\left(1-\frac{ET_a}{ET_c}\right) \quad (1)$$

where ET_a: actual crop evapotranspiration (mm), ET_c: potential crop evapotranspiration (mm), Y_a: actual crop yield (corresponding to ET_a) (kg/ha), Y_m: maximum (theoretical) crop yield (corresponding to ET_c) (kg/ha) and K_y: crop yield response factor to water deficit (-). AquaCrop estimates daily biomass production using Eq. 2:

$$B_i=WP^*\sum\left(1-\frac{Tr_i}{ET_{oi}}\right) \quad (2)$$

where B_i is the daily aboveground biomass, Tr_i is the daily crop transpiration, ET_{oi} is the daily reference evapotranspiration, and WP* is the water productivity of the crop species normalized for both evaporative demand and atmospheric CO_2.

Crop yield was obtained by multiplying aboveground biomass and specified harvest index (HI) using Eq. 3 (Steduto et al., 2009):

$$Y=HI\cdot B \quad (3)$$

where Y is the main yield (kg/ha), B is aboveground biomass (kg/ha), and HI is the harvest index (%). The main components of the AquaCrop model and their relationships are presented in Steduto et al. (2009).

Table 1. Specifications of field experiments used for calibration and validation of models.

Crop	Year of experiment	No. of treatments	Measured parameters	Reference	Application in this study
Maize	2011	3	DW of leaves, stems, and storage organ and LAI	Mirzaee (2013)	Calibration
	2012	4	DW of leaves, stems, and storage organs, LAI, crop canopy cover, and soil moisture	Ahmadpour (2013)	Validation
Soybean	2012	4	DW of leaves, stems, and storage organs, LAI and crop canopy cover	Esmaili (2014)	Calibration
	2015	8	DW of leaves, stems, and storage organs, LAI, crop canopy cover, and soil moisture	Dehghan Moroozeh (2019)	Validation

DW: dry weight. LAI: leaf area index.

DSSAT model

DSSAT is a software application program that can be used for the simulation of more than 40 crops, including maize and soybean. The DSSAT is a collection of independent programs that operate together; crop simulation models are at its center. In this software package, there is a specialized model for each crop. CERES-Maize and CROPGRO-Soybean are examples of these models, respectively, for growth simulation of maize and soybean. The crop simulation models simulate growth, development, and yield as a function of the soil-plant-atmosphere dynamics on a daily basis. The tools include database management programs for soil, weather, crop management and experimental data, utilities, and application programs (Jones et al., 2003).

Study area

The field experiments were conducted in two research farms. The study of 2011 was conducted at the research farm of the Agricultural Organization in Mahidasht, and the studies of 2012 and 2015 were conducted at the research farm of Razi University in Kermanshah, Iran (Fig. 1). The geographical location of the research fields and the average annual rainfall and temperature of Kermanshah and Mahidasht are presented in Table S1. Average monthly weather parameters during the implementation of research projects are presented in Table S2.

The physical characteristics of the soil of the research fields are presented in Table S3. The texture of the soil on the farm of Razi University was finer than that of the Mahidasht Agricultural Organization. The water holding capacity in the research farm of Razi University and the Agricultural Organization was 144 and 104 mm/m, respectively.

Field and laboratory experiments

For each crop, two years of field data were used to calibrate and validate the crop growth simulation models (Table 1). The models were calibrated based on field data from two M.Sc. research projects (Mirzaee, 2013; Esmaili, 2014) and validated based on field data from an M.Sc. (Ahmadpour, 2013) and a Ph.D. research project (Dehghan Moroozeh, 2019), which all were carried out under the supervision of the corresponding author of this paper. The four studies were conducted in the form of a randomized complete block design with a certain number of irrigation treatments and replications. To eliminate marginal effects, a distance of 3 m was considered between the plots. Except for Mirzaee's study, which was conducted in Mahidasht, 25 km away from Razi's research farm, three other experiments were conducted on the research farm of Razi University, Kermanshah, Iran. In the following, the studies of Mirzaee (2013) and Esmaili (2014) will be described briefly, and the studies of Ahmadpour (2013) and Dehghan Moroozeh (2019) will be described in detail.

Mirzaee (2013) conducted a field experiment in 2011 to calibrate crop parameters of the WOFOST (de Wit et al., 2019) model for grain maize. In this experiment, maize was cultivated in three irrigation treatments (100%, 80% and 60% of irrigation requirement) with three replications. This experiment was conducted in the research farm of the agricultural organization in Mahidasht, Kermanshah,

Figure 1. Location of the experimental fields at Kermanshah province, Iran.

Table 2. Specifications of the irrigation treatments in the studies of Ahmadpour (2013) and Dehghan Moorozeh (2019).

Crop	Treatment	Irrigation depth (% of crop water requirement)	Period of deficit irrigation	Total depth of applied water (mm)	Reference
Soybean	T1	100	---	842	Dehghan Moorozeh (2019)
	T2	120	---	960	
	T3	80	Whole period	724	
	T4	60	Whole period	605	
	T5	80	Vegetative phase	827	
	T6	60	Vegetative phase	797	
	T7	80	Reproductive phase	746	
	T8	60	Reproductive phase	650	
Maize	T1	100	---	828	Ahmadpour (2013)
	T2	120	---	946	
	T3	80	Whole period	710	
	T4	60	Whole period	593	

Iran, located 25 km away from the Faculty of Agriculture, where other studies were conducted. The altitude of this station is 1365 masl. The weather parameters in this study were given from a weather station which was located in the region. During the growth period, the dry weight (DW) of leaves, stems, and storage organs and leaf area index (LAI) were measured weekly in each plot. The average biomass, grain, and LAI in each irrigation treatment were used for model calibration.

Esmaeili (2014) conducted a field experiment in 2012 to calibrate the crop parameters of AquaCrop for soybean. This experiment was conducted in four irrigation treatments (120%, 100%, 80%, and 60% of irrigation requirement) with four replications. In this experiment, the DW of leaves, stems, and storage organs, LAI, and green canopy cover were measured every ten days. The average of crop parameters in each irrigation treatment was used for calibration of crop models of AquaCrop and DSSAT for soybean.

The experiment conducted in Ahmedpour's study (Ahmadpour, 2013) was performed in four irrigation treatments with three replications for maize (Table 2). In this experiment, 12 plots with a size of 5 × 6 m were cultivated with a row distance of 75 cm (Fig. 2a).

Dehghan Moorozeh (2019) studied the impacts of deficit irrigation on soybean yield and crop water productivity based on his field experiments in 2015. In this study, soybean was cultivated in 24 plots with the size of 4 × 4 m with a row spacing of 50 cm. The number of irrigation treatments and replications was 8 and 3, respectively (Table 2 and Fig. 2b).

During the growth period, crop parameters required for calibration and validation of crop growth simulation models were measured. Green canopy cover, LAI, DW of above-ground biomass, and grain were measured every seven (only in Mirzaee's study) or ten days. In each sampling, three plants from each plot were harvested at predetermined locations and transported to the laboratory. In the laboratory, different parts of the plant (leaf, stem, and grain) were separated to measure each part separately. The leaves were scanned using a scanner (Epson Perfection V39 Scanner) with a resolution of 4800 dpi. The area of green leaves was calculated using image analysis. The LAI was calculated as the ratio of green leaf area per area allocated to each plant. Leaves, stems, and grains of the harvested plants were dried in the oven at 70 °C for 48 h and then weighed. The sum of the DW of leaves, stems and grain was considered as total above-ground biomass. In this paper, the measured and simulated crop yield (biomass and grain) are reported in terms of DW. The percentage of green canopy cover was estimated based on the analysis of photos taken over the top of the crop canopy.

Soil moisture is a key output of water-related crop growth simulation models. Unfortunately, this parameter was not measured in the studies of Mirzaee and Esmaeili. But, this parameter was measured in the studies of Ahmadpour and Dehghan Moorozeh which were used for validation of models. The soil moisture was measured one day

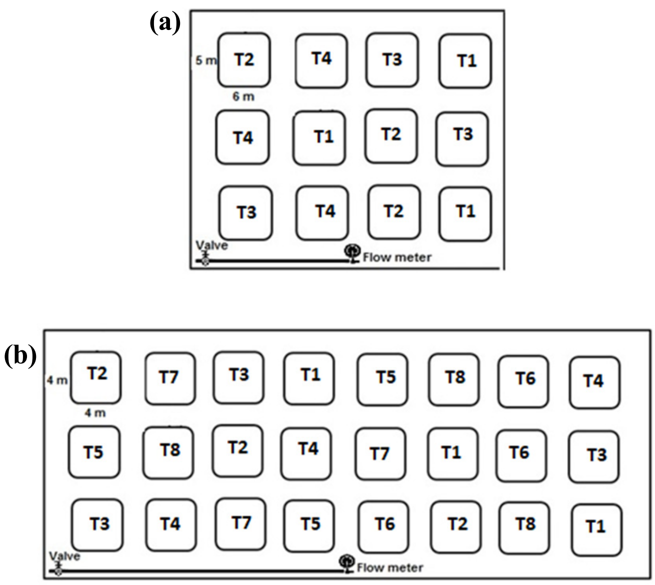

Figure 2. Schematic map of experimental treatments for a) maize and b) soybean.

before irrigation using the gravimetric method (Johnson, 1962) at depths of 15 and 45 cm for maize (Ahmadpour, 2013) and at depths of 15, 45, and 60 cm for soybean (Dehghan Moroozeh, 2019). Due to laboratory limitations, soil moisture was measured only in T1, T2, T3, and T4 treatments for soybean and T1, T3, and T4 for maize. Moreover, phenological growth stages (e.g., dates of crop emergence, flowering, the start of seed filling, the start of senescence, and maturity) were determined based on daily observations.

Irrigation treatments

Irrigation treatments were defined as a certain percentage of crop water requirement. For this purpose, first reference crop evapotranspiration (ETo) was calculated based on the FAO Penman-Monteith equation (Allen et al., 1998) (Eq. 4).

$$ET_o = \frac{0.408\Delta R_n + \gamma \dfrac{900}{T_a + 273} U_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34\, U_2)} \quad (4)$$

where ETo is the reference crop evapotranspiration (mm/d); Δ is the slope of saturation vapor pressure (kPa/°C); R_n is the daily net radiation ($MJ/m^2 \cdot d$); G is the soil heat flux ($MJ/m^2 \cdot d$); γ is the psychometric constant (kPa/°C); T_a is the mean air temperature at 2 m height (°C); U_2 is the daily mean of wind speed at 2 m height (m/s); e_s is the saturation vapor pressure (kPa); and e_a is the actual vapor pressure (kPa).

All the weather parameters needed to calculate ETo were obtained from nearby weather stations. Crop evapotranspiration (ETc) was calculated by multiplying ETo by the crop coefficient (Kc) provided in the National Water Document (Agri-PERI, 2017) for the study area.

Since there was no rainfall during the period of application of the treatments, the crop water requirement was considered equal to ETc. Considering the soil physical parameters of the research farm and crop water requirement, the irrigation interval was considered seven days for both crops. In all four studies, deficit irrigation was not applied in the early stages of crop growth to ensure crop establishment. For this purpose, in the first four irrigations, the irrigation interval was considered three days, and the amount of applied water was equal for all treatments. So, the plots were irrigated weekly except in the crop establishment period, in which the irrigation interval was three days. The volume of required water in the control treatment (T1) was calculated based on accumulated crop water requirements since the last irrigation and plot size. The irrigation volume of other treatments was calculated based on the control treatment. The applied water in the treatments of T1, T2, T3, and T4 was 100%, 120%, 80% and 60% of the crop water requirement, respectively. In treatments of T5 and T6, which were applied for soybean, 20% and 40% deficit irrigation was implemented only in the vegetative phase (no water stress was applied in the reproductive stage). In treatments of T7 and T8, deficit irrigation was implemented only in the reproductive stage (Table 2). The reason for choosing T2 treatment (120% of crop water requirement) was the uncertainty of the estimated ETo by the Penman-Monteith formula in the study area (Esmaeili et al., 2015; Ahmadpour et al., 2017). The required amount of water was applied using a hose connected to a flowmeter with an accuracy of 0.1 liters (Furrow irrigation). The crop management (e.g., land preparation, fertilizer, weed & pest management) was implemented under the supervision of an agronomist.

Calibration and validation

Crop, weather/climate, soil, and management files are required as model inputs for both models. Soil files were created based on the soil physical properties of the research farm (Table S3). Daily weather data in the study area was used to prepare the weather/climate files. For each treatment, a management file that contains the time and depth of irrigation was also created. Crop files/parameters are required to run the models. Some of the crop parameters are variety-specific and should be determined or calibrated.

In the calibration process, first, the phenological dates were set based on the full irrigation treatment. Then the crop parameters were changed by trial and error so that there was a slight difference between the simulated parameters and the measured average in all treatments. Three parameters were used to calibrate the models. The average

Table 3. Calibrated crop parameters of soybean and maize (AquaCrop model).

Parameter	Unit	Soybean	Maize	Comments
Percentage of canopy cover decline rate	% per day	4	7	Calibrated
Percentage of canopy cover growth rate	% per day	9.4	13.4	Experimental
Upper threshold of soil available water that stresses canopy cover development	-	0.65	0.45	Calibrated
Lower threshold of soil available water that stops canopy cover development	-	0.15	0.15	Calibrated
Shape factor of stress on leaf development	-	1.5	3	Calibrated
Upper threshold of soil available water that stresses the crop by closing the stomata	-	0.27	0.20	Calibrated
Shape factor of stress after stomata closure	-	1.9	2	Calibrated
Upper threshold of soil available water that leads to stress or early senescence	-	0.35	0.28	Calibrated
Shape factor of stress after early senescence	-	1.77	6	Calibrated
Upper threshold of soil available water that leads to stress in flowering stage	-	0.78	0.76	Calibrated
Maximum crop coefficient	-	1	1.1	Calibrated
Base temperature below which crop development does not progress	°C	5.0	8.0	Default
Duration from cultivation to emergence	degree-day	90	112	Experimental
Duration from cultivation to flowering	degree-day	530	970	Experimental
Duration from cultivation to start of senescence	degree-day	870	1436	Experimental
Duration from cultivation to physiological maturity	degree-day	1160	1844	Experimental
Duration from cultivation to maximum canopy cover	degree-day	770	988	Experimental
Duration from cultivation to maximum root depth	degree-day	920	1436	Experimental
Duration of flowering stage	degree-day	480	421	Experimental
Maximum harvest index	%	24	38	Experimental

grain yield, biomass, and crop canopy cover in each treatment and sampling day were used for AquaCrop calibration. For DSSAT, the LAI was used instead of crop canopy cover.

Field data collected by Ahmadpour (2013) and Dehghan Moroozeh (2019) were used to validate the calibrated models. According to the measurement of soil moisture in the latest studies, soil moisture was used in addition to the mentioned parameters in the validation process. The simulated biomass, grain yield, and LAI/green canopy cover at sampling dates were compared with measured data graphically and statistically. Although graphical comparisons were made for the three crop parameters, only graphs related to biomass are presented in the paper. Usually, statistical indices are used for the assessment of model validation. Yang et al. (2014) evaluated a group of deviation statistics that are commonly used for crop model calibration and validation. In this study, statistical indices of Normalized Root Mean Square Error (nRMSE) and Nash-Sutcliffe Model Efficiency (EF), which are among the suggested deviation statistics by Yang et al. (2014), were used to model evaluation (Eqs. 5 and 6):

$$nRMSE = 100\left(\frac{\sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}}}{O_{ave}}\right) \quad (5)$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O_{ave})^2} \quad (6)$$

where O_i is observed data, P_i is simulated data by the model, O_{ave} is the mean of the observed data.

Lower values of nRMSE and higher values of EF indicate better performance of the model. The range of nRMSE

Table 4. Calibrated genotype parameters of soybean (DSSAT model).

Parameter	Parameter description	Value
CSDL	Critical short day length below which reproductive development progresses with no daylength effect (for shortday plants) (hour)	13.4
PPSEN	Slope of the relative response of development to photoperiod with time (positive for shortday plants) (1/hour)	0.29
EM-FL	Time between plant emergence and flower appearance (R1) (photothermal days)	45
FL-SH	Time between first flower and first pod (R3) (photothermal days)	7
FL-SD	Time between first flower and first seed (R5) (photothermal days)	16
SD-PM	Time between first seed (R5) and physiological maturity (R7) (photothermal days)	34.5
FL-LF	Time between first flower (R1) and end of leaf expansion (photothermal days)	26
LFMAX	Maximum leaf photosynthesis rate at 30 C, 350 vpm CO_2, and high light (mg CO_2/m^2-s)	1.03
SLAVR	Specific leaf area of crop under standard growth conditions (cm^2/g)	375
SIZLF	Maximum size of full leaf (three leaflets) (cm^2)	180
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	1
WTPSD	Maximum weight per seed (g)	0.11
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	23
SDPDV	Average seed per pod under standard growing conditions (#/pod)	2.2
PODUR	Time required for crop to reach final pod load under optimal conditions (photothermal days)	10
THRSH	Threshing percentage. The maximum ratio of (seed/(seed+shell)) at maturity. Causes seeds to stop growing as their dry weight increases until shells are filled in a cohort.	77
SDPRO	Fraction protein in seeds (g(protein)/g(seed))	0.41
SDLIP	Fraction oil in seeds (g(oil)/g(seed))	0.21

is between 0 and 100%. Jamieson et al. (1991) rated model performance based on nRMSE as excellent (< 10%), good (between 10% and 20%), fair (between 20% and 30%), or poor (> 30%).

Results and discussion

DSSAT and Aquacrop models were calibrated based on the measured grain yield, biomass, and crop canopy/

Table 5. Calibrated genotype parameters of maize (DSSAT model).

Parameter	Parameter description	Value
P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8 °C) during which the plant is not responsive to changes in photoperiod	280
P2	Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h)	0.4
P5	Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 °C)	850
G2	Maximum possible number of kernels on topmost ear	750
G3	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day)	6.8
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances	38.9

Table 6. Statistical indicators in estimating soybean crop parameters by DSSAT and AquaCrop models.

Statistical index	Treatment	Biomass		Grain		LAI	Crop canopy
		DSSAT	AquaCrop	DSSAT	AquaCrop	DSSAT	AquaCrop
nRMSE	T1	10.7	17.2	15.0	34.4	14.9	17.1
	T2	21.1	24.8	8.5	26.2	11.9	17.5
	T3	21.7	13.8	24.7	27.9	16.0	23.0
	T4	25.3	62.3	28.3	45.9	14.4	18.4
	T5	22.2	35.6	11.7	41.9	13.6	32.7
	T6	17.4	24.3	8.4	31.5	7.7	29.6
	T7	23.4	26.4	7.5	28.1	15.7	17.4
	T8	19.7	38.6	23.8	35.6	17.2	22.5
	Average	20.2	30.4	16.0	33.9	13.9	22.3
EF	T1	0.97	0.89	0.97	0.48	0.94	0.75
	T2	0.92	0.86	0.98	0.72	0.96	0.76
	T3	0.94	0.87	0.96	0.54	0.94	0.59
	T4	0.88	0.45	0.96	0.45	0.94	0.69
	T5	0.92	0.83	0.98	0.68	0.95	0.55
	T6	0.95	0.88	0.98	0.6	0.99	0.41
	T7	0.91	0.79	0.98	0.44	0.92	0.79
	T8	0.93	0.40	0.97	0.41	0.92	0.46
	Average	0.93	0.75	0.97	0.54	0.95	0.63

nRMSE: normalized root mean square error. EF: Nash-Sutcliffe model efficiency. LAI: leaf area index.

LAI in the studies of Mirzaee (2013) and Esmaeili (2014). First, the phenological parameters were determined based on field observations and weather data. Then, by trial and error, other crop parameters were determined to have the minimum difference between the measured and simulated grain yield, biomass, and crop canopy/LAI at the time of field measurements for all treatments. The calibrated crop parameters for both models and crops are reported in Tables 3, 4, and 5.

The results of the field experiments conducted in the studies of Ahmadpour (2013) and Dehghan Moroozeh (2019) were used to assess the accuracy of calibrated models under water stress conditions. Measured grain yield, biomass, canopy/LAI, and soil moisture at two (maize) or three (soybean) depths during the crop growth period were compared with data estimated by crop growth simulation models. Although comparisons were made for all the measured parameters, only graphical comparisons are presented for biomass. Of course, statistical comparisons are provided for all parameters.

The maximum biomass and grain yield of soybean in the T2 treatment (120% irrigation) were 11,180 and 2,140 kg/ha, respectively (Fig. 3), which is higher than in T1 (control treatment). It seems that the crop water requirement of soybean is underestimated by the FAO-Penman Monteith formula. Similar results have been reported by

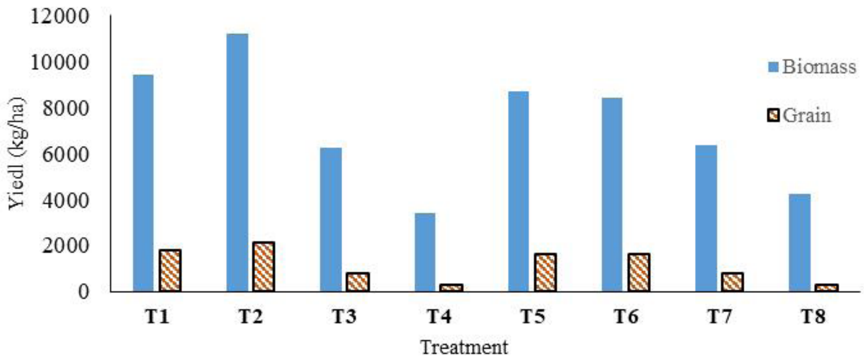

Figure 3. Measured final biomass and grain yield of soybean (kg/ha).

Table 7. Statistical indices in estimating soil moisture (cm^3/cm^3) at depths of 15, 45, and 60 cm in the soybean.

Index	Treatment	DSSAT				AquaCrop			
		15	45	60	Average	15	45	60	Average
nRMSE	T1	5.0	8.1	8.2	7.1	5.3	10.1	10.1	8.5
	T2	5.3	5.6	8.6	6.5	5.5	5.8	9.7	7.0
	T3	4.7	5.0	7.8	5.8	10.1	10.1	10.1	10.1
	T4	8.0	5.0	1.0	4.7	7.9	5.1	5.1	6.0
	Average	5.75	5.9	6.4	6.0	7.2	7.7	8.8	7.9
EF	T1	0.72	0.61	0.64	0.66	0.69	0.21	0.46	0.45
	T2	0.52	0.78	0.52	0.61	0.48	0.69	0.39	0.52
	T3	0.88	0.77	0.73	0.79	0.47	0.66	0.55	0.56
	T4	0.40	0.79	0.99	0.73	0.41	0.73	0.76	0.63
	Average	0.63	0.74	0.72	0.70	0.51	0.57	0.54	0.54

nRMSE: normalized root mean square error. EF: Nash-Sutcliffe model efficiency.

Ahmadpour et al. (2017) and Esmaeili et al. (2015) in the study area. Final biomass in treatments T1, T5, and T6 had differences lower than 10%. The reason is related to small differences between the amount of applied irrigation in these treatments (Table 2) as irrigation treatments were not implemented during the crop establishment period, which is part of the vegetative stage. The lowest yield was observed in treatment T4 (40% deficit irrigation in the whole crop growth period).

The measured and simulated soybean biomass for the studied treatments is shown in Fig. 4. Although both models express soybean biomass production trends relatively well, DSSAT shows a better estimation in all treatments than AquaCrop. In water stress treatments (especially in those with stress in the reproductive phase), the deviation between the measured soybean biomass and the simulated by the AquaCrop model increased. Giménez et al. (2017) reported poor accuracy of AquaCrop in the simulation of grain yield of soybean. Adeboye et al. (2017) showed that the AquaCrop model performed better in simulating the dry biomass of soybean for full irrigation than for deficit irrigation.

Statistical indices of nRMSE and EF were calculated for soybean crop parameters for all treatments (Table 6). The average of statistical indices indicated the better performance of DSSAT in the simulation of soybean growth than AquaCrop. The average of nRMSE indicates good performance (Jamieson et al., 1991) of the DSSAT model in the simulation of LAI, biomass, and grain (Table 6). The same results are obtained based on the EF index. The average EF for DSSAT and AquaCrop models were in the range of 0.92–0.97 and 0.54–0.75, respectively. Considering statistical analysis, it can be concluded that DSSAT performed better than AquaCrop in the simulation of soybean growth. Similar results were also reported by Battis-

Table 8. Statistical indicators in estimating maize crop parameters by DSSAT and AquaCrop models.

Statistical index	Treatment	Biomass		Grain		LAI	Crop canopy
		DSSAT	AquaCrop	DSSAT	AquaCrop	DSSAT	AquaCrop
nRMSE	T1	22.4	9.3	15.8	33.8	20.8	7.8
	T2	10.6	10.1	21.4	25.6	16.4	6.0
	T3	37.3	18.4	20.0	18.7	22.2	12.1
	T4	35.2	15.0	37.0	30.3	28.3	13.2
	Average	26.4	13.2	23.6	27.1	21.9	9.8
EF	T1	0.94	0.99	0.94	0.72	0.91	0.99
	T2	0.99	0.99	0.72	0.82	0.94	0.99
	T3	0.76	0.94	0.88	0.90	0.88	0.96
	T4	0.85	0.97	0.57	0.71	0.82	0.95
	Average	0.88	0.97	0.86	0.94	0.89	0.97

nRMSE: normalized root mean square error. EF: Nash-Sutcliffe model efficiency. DW: dry weight. LAI: leaf area index.

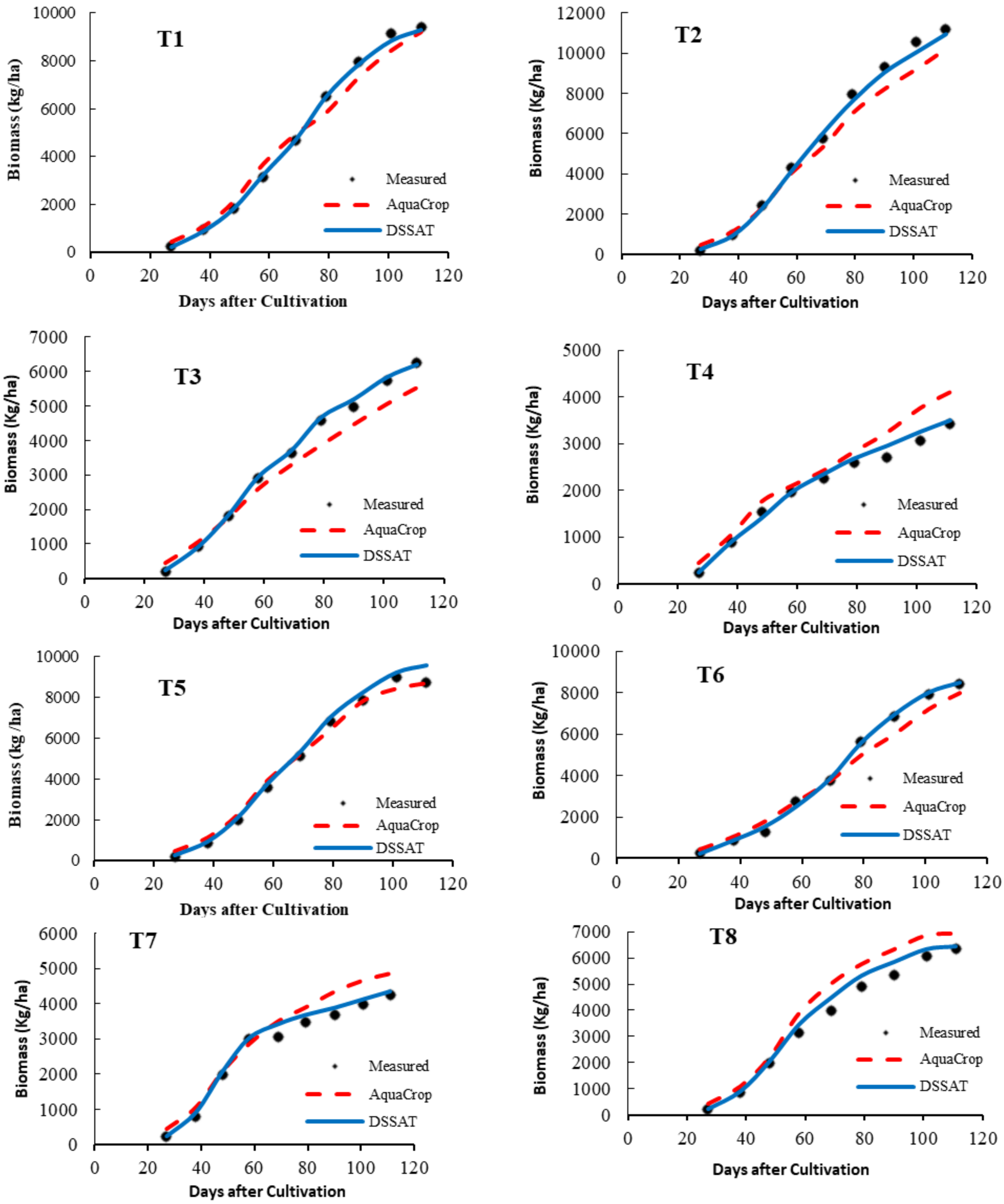

Figure 4. Measured and simulated soybean biomass with DSSAT and AquaCrop models.

ti et al. (2017), who found a better performance of DSSAT than AquaCrop in terms of soybean grain estimation. The result of this study is also in agreement with Kumar et al. (2008) and Ovando et al. (2018), who reported acceptable accuracy of CROPGRO in the simulation of soybean crop growth and yield. The performance of the models was lower in T4, where the crop was under severe water stress.

The statistical indices of nRMSE and EF for soil moisture at depths of 15, 45, and 60 cm in the soybean experiment are reported in Table 7. The lower nRMSE and higher EF in the DSSAT model indicate the better performance of this model in soil moisture estimation than the AquaCrop model. The results indicated a better estimate of soil moisture at a depth of 45 cm.

Table 9. Statistical indices in estimating soil moisture at depths of 15 and 45 cm in the maize field.

Index	Treatment	DSSAT			AquaCrop		
		15	45	Average	15	45	Average
nRMSE	T1	3.0	4.0	3.5	2.9	2.5	2.7
	T3	5.1	2.1	3.6	4.7	2.0	3.3
	T4	3.4	3.7	3.6	2.9	2.4	2.7
	Average	3.8	3.2	3.5	3.5	2.3	2.9
EF	T1	0.72	0.65	0.7	0.73	0.45	0.6
	T3	0.50	0.40	0.4	0.58	0.45	0.5
	T4	0.52	0.31	0.4	0.65	0.65	0.7
	Average	0.58	0.45	0.50	0.65	0.52	0.60

nRMSE: normalized root mean square error. EF: Nash-Sutcliffe model efficiency.

The highest and lowest maize yield was observed respectively in T2 and T4. As in soybean, the maximum crop yield of maize was observed in T2 (120% irrigation). Considering the underestimation of crop water requirement by FAO-56 Penman Monteith equation for both studied crops (soybean and maize), the initial assumption regarding the definition of 120% irrigation treatment was reasonable. Therefore, it is suggested that in cases where crop water requirement is estimated using FAO-56 Penman Monteith equation, treatment of 20% of over-irrigation is recommended.

The measured and simulated maize biomass by DSSAT and AquaCrop is presented in Fig. 5. These graphs show the better simulation of maize biomass by the AquaCrop model. Although the biomass simulated by the DSSAT model is accurate in T2 treatment, the accuracy of this model is lower in other treatments.

The statistical analysis between measured and simulated parameters also indicated the better overall performance of AquaCrop in the simulation of maize than CERES-Maize in the study area (Tables 8 and 9). These results are consistent with Ziaii et al. (2014) and Mibulo & Kiggundu (2018). The accuracy of both models in simulating maize grain yield was lower than biomass and LAI/crop canopy cover (Table 8), which is in conformity with the results of Liu et al. (2011) and is inconsistent with other studies such as Heng et al. (2009). The reason could be due to the measurement error of the grain in the early stage of the grain formation period. The comparison of EF model efficiency in Tables 8 and 9 shows the lower efficiency of both models in estimating soil moisture compared to biomass, grain yield, and LAI. Since soil moisture was not measured in the studies used for model calibration, the soil moisture results should be considered with caution (for both crops).

Conclusions

Although crop growth simulation models are useful tools for simulating the impact of environmental parameters on crop yield and water requirements, the use of these models is limited in developing countries such as Iran. The need to calibrate the (crop) parameters of these models is one of the limiting factors of their use. Due to the diversity of available models and disagreements about the appropriate model, the limited studies conducted in these areas are scattered and not very practical. In this study, crop parameters of AquaCrop and DSSAT crop growth simulation models were calibrated and validated based on two-year measured yield (biomass and seed), and leaf area/crop canopy index. It is better to use these data to evaluate the performance of other crop models (e.g. WOFOST). Two years of data could be the minimum data to calibrate and validate these models. Therefore, it is suggested that agricultural research centers have a program for the calibration and validation of crop growth simulation models and use multi-year data for this purpose.

In this study, the performance of AquaCrop and DSSAT crop growth simulation models was investigated under full and deficit irrigation conditions. The results showed that in the study area, the overall performance of AquaCrop in estimating crop yield and soil moisture for maize was better than DSSAT, while the performance of DSSAT for soybean was better than AquaCrop. The accuracy of the models in the condition of deficit irrigation was lower than that of full irrigation. Therefore, it is not possible to propose a specific model to simulate the growth of all crops in a region. Choosing the appropriate model depends on the crop type, environmental conditions, and the purpose of the study.

Although determining the crop water requirement has been the focus of many studies for decades, the appropriate method for estimating ETo for many regions has not yet been identified. This issue can also be a limiting factor in the use of crop growth simulation models. In this study, the FAO Penman-Monteith formula, which many researchers believe is the most appropriate method for estimating ETo,

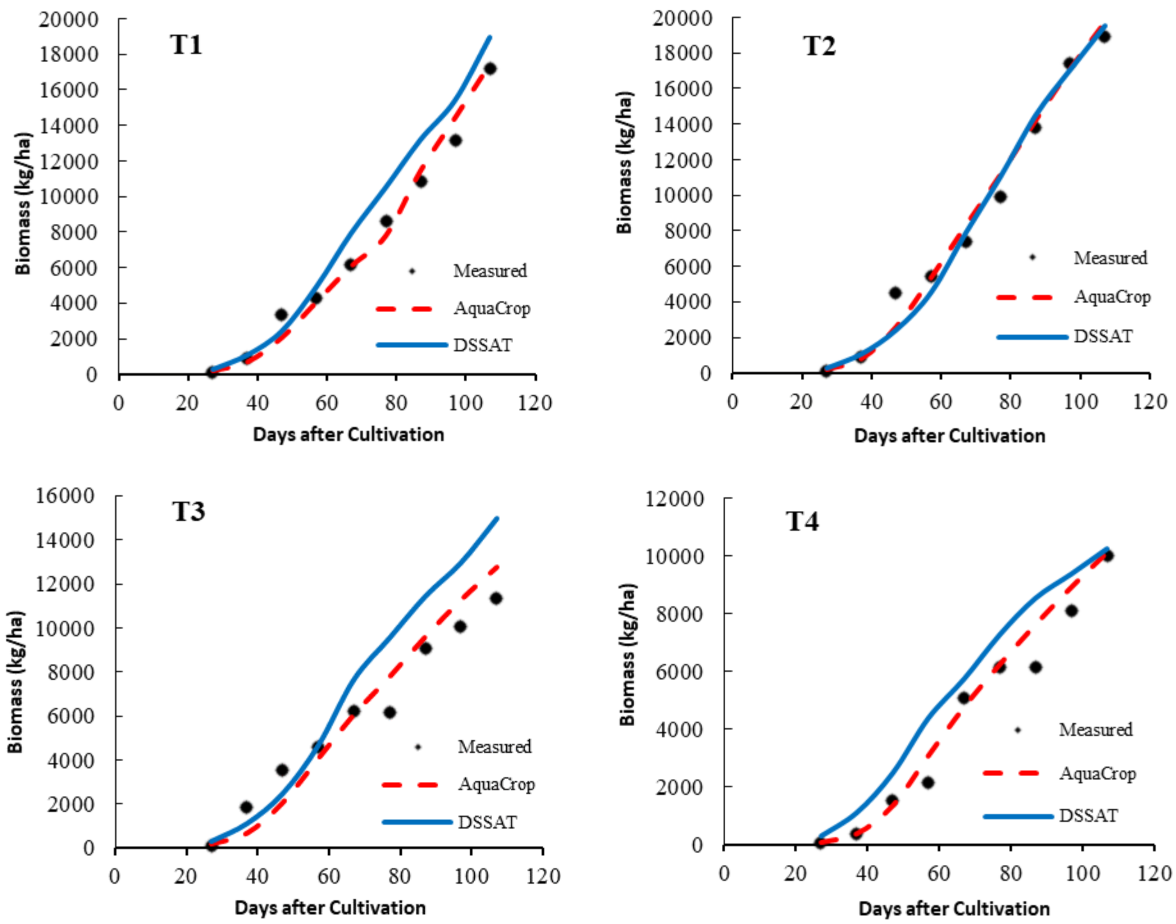

Figure 5. Measured and simulated biomass of maize in the validation stage for treatments T1-T4 with DSSAT and AquaCrop models.

was used to determine crop water requirements. The results showed that this formula underestimates the amount of ETo in the conditions of the study area. Therefore, we recommend treatments of 20% over-irrigation in similar studies.

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Writing – original draft: A. Dehghan Moroozeh
Writing – review & editing: B. Farhadi Bansouleh, M. Ghobadi

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