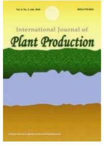

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Safflower model for simulation of growth and yield under various irrigation strategies, planting methods and nitrogen fertilization

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Abstract

Development and use of crop growth models is an effective tool for agricultural planning and decision making in agricultural industry. Besides, the drought and limited supplies of water in many areas of the world has increased attention to favourable strategies in farm management such as efficient irrigation and planting methods. The objective of this study was to develop a crop model for safflower known as a multi-purpose crop under various irrigation regimes, planting methods and nitrogen fertilization. The experiment was designed as split-split plot that arranged in randomized complete blocks with irrigation strategy as the main plot, planting method as the subplot and nitrogen levels as the sub-subplot in three replications. The irrigation strategies consisted of ordinary furrow irrigation (OFI) and variable alternate furrow irrigation (VAFI) as a partial root drying (PRD) technique. The planting methods were on-ridge planting (P_1) and in-furrow planting (P_2) methods. The fertilizer levels were 0 (N_0), 100 (N_1) and 200 (N_2) kg ha^{-1} of urea as 0, 46 and 92 kg N ha^{-1}. Two years of the experiment carried out in a semi-arid area from 2012 to 2014. The field data of the second year of experiment were used to develop the model and it was validated by the data of first year. The results indicated that the proposed safflower model is able to estimate evapotranspiration, soil water content, leaf area index, soil surface evaporation, crop transpiration, biomass, straw and seed yield of safflower in an appropriate manner. The safflower model is useful for having better field management and reducing administrative costs with respect to the model simplicity and its briefness in data input.

Keywords: Crop modeling; PRD irrigation; Alternate furrow irrigation; Leaf area index; Evapotranspiration.

Introduction

The agricultural scientists and decision makers are involved in challenges to ensure the sustainable agricultural productivity against the population increase across the globe. Since, the traditional field experiments are expensive and time consuming, the development and use of crop growth models are essential for agricultural planning and decision makings in food production industry (Murthy, 2004). Furthermore, simulation of crop response to production factors has been the interest of farmers and agricultural scientists for a long time for better scheduling and more efficient management of crop production processes (Zand-Parsa et al., 2006). There are many crop models that have developed under various purposes and situations. Generally, the complex models need various on-farm measurements for estimation of crop yields that are often non-accessible or over-detailed than necessary data (Smith, 1992; Yin et al., 2000; Ziaei and Sepaskhah, 2003). On the other hand, simple models which can estimate the crop growth and yield are therefore an advantage and can be easily used for practical applications using simple equations and fewer input data (Sepaskhah et al., 2013; Sepaskhah et al., 2006). In this respect, there are some simple crop models for rapeseed, maize and saffron that have developed by Shabani et al. (2015), Bagheri et al. (2014) and Sepaskhah et al. (2013), respectively.

Safflower is an oilseed crop that was originated from Middle East and South Asia and it is currently grown in many areas of the world. Traditionally, safflower was used for colouring and flavouring foods and dyeing cloths; however, now it is commonly used in edible oil, spices, birdfeed, cosmetics and some medicinal applications. Furthermore, new researches on safflower have initiated recently, due to its potential for using as bio-fuels and diesel fuel. Application of proper management policies on safflower may lead to higher productions and lower use of resources. Indeed, the scarce water resources and limited eligible land for cultivation against growth of human population, increasing the production capacity of the cultivated lands and enhancement of water use efficiency are necessary issues that mainly are achievable by application of fertilizers, efficient irrigation strategies and planting methods. In this respect, variable alternate furrow irrigation (VAFI) as a partial root drying (PRD) technique has been recognized as an efficient irrigation technique in arid and semi-arid regions for having higher water saving and water productivity (Horst et al., 2007; Thind et al., 2010; Slatni et al., 2011). Besides, choosing proper planting methods such as in-furrow planting can be another useful strategy to have higher water saving in arid and semi-arid regions (Shabani et al., 2013; Yarami and Sepaskhah, 2015; Shahrokhnia and Sepaskhah, 2016). Furthermore, application of appropriate amount of water, nitrogen fertilizer and management strategies are important in order to maximize their application efficiency and crop production increase.

The objective of this study was to develop a simple model for simulating the growth and yield of safflower under different irrigation strategies, planting methods and N application rates using soil water budget and other simple relationships for evapotranspiration partitioning, leaf area index determination and dry matter-transpiration function, harvest index and seed yield relationship.

Materials and Methods

Field experiment

Site description and experimental design

This study was conducted in the Experimental Research Station of the Agricultural College, Shiraz University in Iran during 2012–2013 and 2013–2014 growing seasons. This station is located in Badjgah area at 29° 56’ N latitude, 52° 02’ E longitude and 1810 m above mean sea level in a semi-arid area. The climate parameters (rainfall, maximum and minimum temperatures, maximum and minimum relative humidity, wind velocity, sunshine hours, pan evaporation) were recorded in a weather station near the site. The mean monthly climatic data for the two years of experiment have reported in Figure 1. Rainfall events were mostly occurred during November to May for both years of study as 433 and 276 mm for the first and second year, respectively. Higher depths of precipitation were observed in November, December and April of 2012-2013 and November and January of 2013-2014. The mean minimum temperature was below zero from December to February of both years and they were in lower values in second year of experiment due to having snowfalls in comparison with the first year. The mean relative humidity was about 45% during the experiment and it was lower in second year compared with the first year of study. The properties of soil and irrigation water are presented in Table 1.

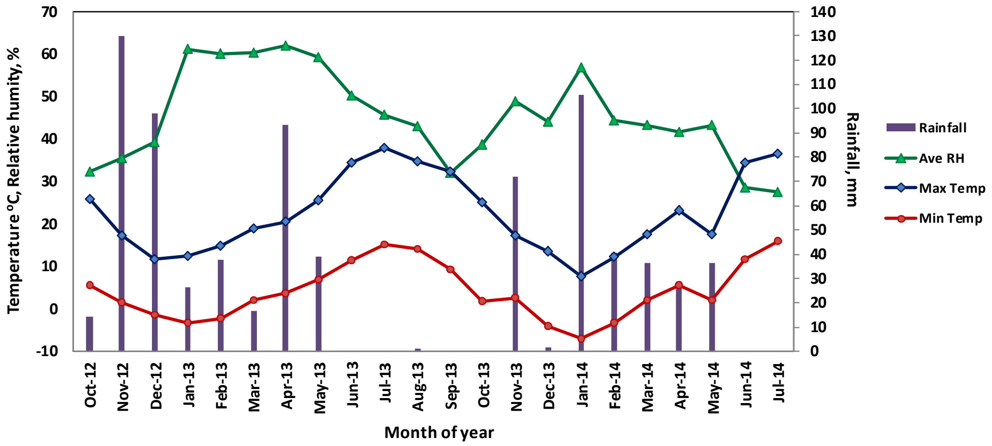

Figure 1. The average of maximum and minimum air temperature and relative humidity with rainfall in years 2012–2014.

Table 1. Soil physical properties and chemical analysis of irrigation water at experimental site.

Soil Characteristic	Unit	Depth (cm)		
		0-30	30-60	60-90
Sand	%	35	23	21
Silt	%	35	38	39
Clay	%	30	39	40
Bulk density (BD)	$g\ cm^{-1}$	1.39	1.44	1.47
Field capacity (FC)	$cm^3\ cm^{-3}$	0.32	0.34	0.36
Permanent wilting point (PWP)	$cm^3\ cm^{-3}$	0.11	0.14	0.16
Organic matter	%	2.6	2.0	1.1
Irrigation water characteristics	Unit	Value		
EC	$dS\ m^{-1}$	0.718		
pH	-	7.58		
Cl^-	$meq\ l^{-1}$	0.9		
Na^+	$meq\ l^{-1}$	0.62		
K^+	$meq\ l^{-1}$	0.03		
Ca^{2+}	$meq\ l^{-1}$	3.9		
Mg^{2+}	$meq\ l^{-1}$	3.0		
HCO_3^-	$meq\ l^{-1}$	4.1		
SO_4^{2-}	$meq\ l^{-1}$	2.5		
NO_3^-	$mg\ l^{-1}$	6.8		
NH_4	$mg\ l^{-1}$	0.0		
PO_4	$mg\ l^{-1}$	0.0		

Three experimental factors were investigated for safflower crop in split-split-plot design that were arranged as randomized complete blocks in three replications. The experimental factors were irrigation strategies, planting method and nitrogen fertilizer application rates. Two different irrigation treatments as the main plot were full irrigation by ordinary furrow (OFI) and the variable alternate furrow irrigation (VAFI) as a partial root drying (PRD) strategy. Seed planting methods were the sub plot as on-ridge planting (P_1) and in-furrow planting (P_2). Fertilizer treatments were the sub-sub plot consisted of three different nitrogen application rates as N_0=0, N_1=100 and N_2=200 kg ha^{-1} of urea fertilizer (0, 46 and 92 kg N ha^{-1}).

Agricultural and irrigation practices

Safflower seed (local Isfahan cultivar) was planted on 25 and 10 October of 2012 and 2013, respectively in 36 water balance lysimeters with barley as the preceding crop. Each lysimeter dimensions was 1.5 m×1.5 m×1.1 m. A layer of 0.05 m gravel was placed at the bottom of each unit and soil layer with height of 0.90 m was placed on top of the gravel layer. The drainage water from the bottom of each lysimeter was conducted into individual sumps by a drain tube and collected. The triple superphosphate (46% P_2O_5) at rate of 100 kg P_2O_5 ha^{-1} and cow manure (2.5 Mg ha^{-1}) were mixed with the soil about two weeks before planting. Afterward, three furrows with 0.5 m spacing and four ridges with 0.5 m spacing and 0.15 m height were made in each lysimeter. Safflower seeds were hand-planted in rows with space of 0.50 m apart and distance of 0.10 m in each row with equal number of plants in each lysimeter. The nitrogen source (urea) for each plot was calculated based on the experimental application rates of nitrogen and was applied to soil at two times in the growing season. Half of the urea was applied at late winter when stem elongation began and the remaining N (50% of requirement) was applied in spring before the flowering stage. In order to prevent the plants from frost damage in December, January and February of both years, lysimeters were covered with a plastic sheet in some freezing nights. Additionally, weeds were removed by hand and aphids were controlled by using appropriate pesticides at several times during the growing period.

Crop irrigation requirement was determined by monitoring the soil water status in different treatments with 7 to 10 days irrigation interval. Soil water content at depths of 0.30 m, 0.60 m and 0.90 m was measured before each irrigation event with neutron scattering method. The access tube of neutron meter was installed in the bottom of middle furrow in OFI and in the bottom of the middle and side furrows of VAFI treatments. The soil water content at depth of 0-0.15 m was determined by gravimetric sampling method. Afterward, soil water contents in the root zone were used to determine the amount of irrigation water. The irrigation water depth was calculated by the following equation:

$$d = \sum_{i=1}^{n} (\theta_{fci} - \theta_i)\Delta z_i \qquad (1)$$

where d is the irrigation water depth (m), θ_{fci} and θ_i are the volumetric soil water content (m^3 m^{-3}) in layer i at field capacity and before irrigation, respectively, Δz_i is the soil layer thickness (m) and n is the number of soil layers. In addition, the crop root depth was estimated during the crop growing season according to the method of Borg and Grimes (1986).

The gross irrigation water depth was determined by using irrigation application efficiency about 75% that is commonly used by farmers for surface irrigation systems. The calculated gross irrigation water depth was fully applied in OFI regimes in all three furrows; whereas, only two third (2/3) of gross irrigation water was applied to the furrow in the VAFI that were dry in the preceding irrigation cycle. Indeed, the amount of irrigation water that is used in alternate furrow irrigation is higher than the half of that in ordinary furrow irrigation because the sided furrows are dry in alternate irrigation and infiltration rate is increased in them. Therefore, the required irrigation water is considered about two third of full irrigation. The amount of irrigation water applied to each lysimeter was measured with a volumetric flow meter. Three initial irrigation events were imposed as full irrigation (OFI) for different treatments to provide uniform seed germination and plant stands. After initial irrigation events, crop water requirement was mostly provided by precipitation until safflower elongation stage that irrigation treatments were started.

Field measurements and analysis

The volume of the collected drainage water from the lysimeters was measured by a volumetric container following each irrigation and rainfall event. Before and after each growing season, soil samples were taken using a tube auger in each lysimeter for measuring nitrate at three depths of 30, 60 and 90 cm. Then, samples were air dried and crushed to pass through a 2 mm sieve. In order to determine soil NO_3-N, the soil samples were extracted in KCl 2M and analysed by cadmium reduction method (Keeney and Nelson, 1982). For determination of leaf area index (LAI), two specified safflower plants were selected from each lysimeter and leaf length (L) and width (W) were measured in about 2-week intervals during the growing season. Furthermore, in different growth stages, some crops were detached from the field and the area of their leaves was measured by an area meter. A relationship between the measured leaf area and multiplication of L×W was determined according to study of Shahrokhnia and Sepaskhah (2017; 2012) and the safflower LAI was obtained by the ratio of total leaf area to ground area devoted to each plant. When safflower matured in July of 2013 and 2014, plants were cut at ground level from two middle rows of lysimeters and then oven dried at 80 ºC. Seeds were separated from straw by crushing. Seed and straw (stems+leaves) were weighted by a balance and yields were determined per unit of area for different treatments. The total biomass was also determined by summation of safflower seed and straw.

Theory of model

The safflower model was mainly developed in this study in order to simulate the growth and yield of safflower under various irrigation strategies, planting methods and nitrogen fertilization. The schematic of the model chart is shown in Figure 2.

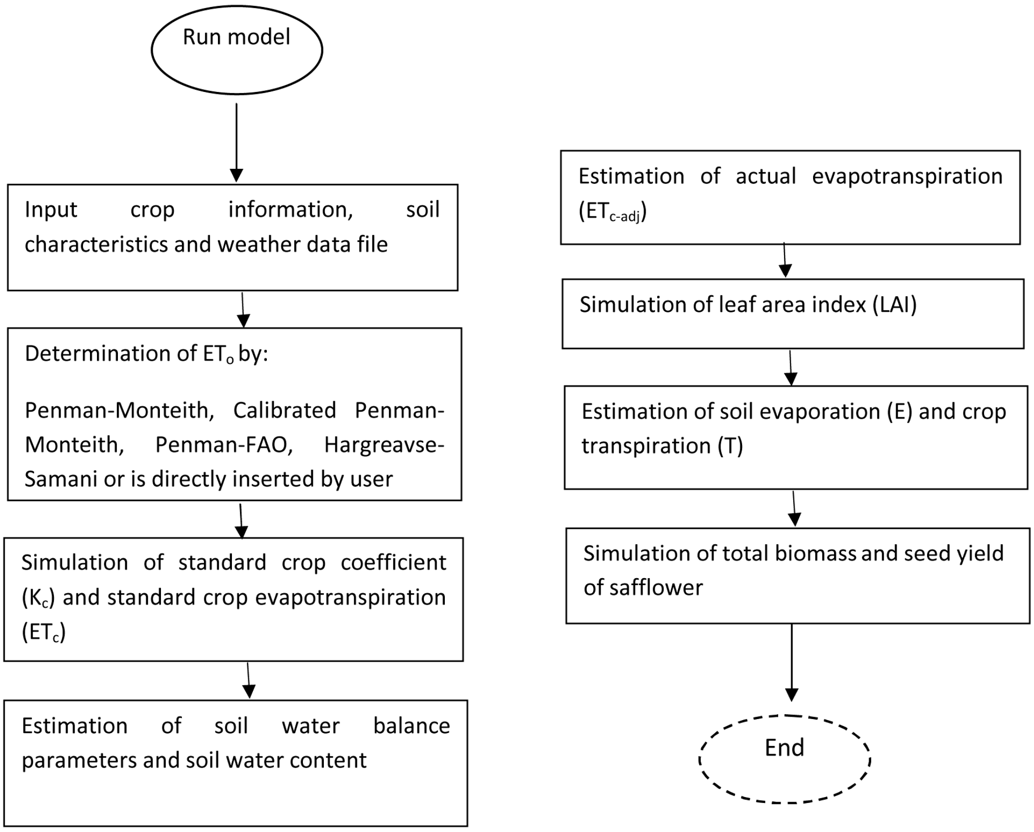

Figure 2. Schematic diagram for safflower model.

Reference evapotranspiration

The reference evapotranspiration (ET$_o$, mm d^{-1}) was determined by choosing one of the different methods including FAO Penman-Monteith [Eq. (2)] (Allen et al., 1998), locally calibrated FAO Penman-Monteith (Razzaghi and Sepaskhah, 2012), FAO-Penman [Eq. (3)] (Doorenbos and Pruitt, 1977), Hargreaves-Samani [Eq. (4)] (Hargreaves and Samani, 1985) equations or its daily values maybe directly inserted into the model by the user.

The equation for reference evapotranspiration (ET$_o$, mm d^{-1}) by FAO Penman-Monteith (Allen et al., 1998) is as follows:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\left[890/(T+273)\right]U_2(e_s - e_a)}{\Delta + \gamma(1+0.34U_2)} \tag{2}$$

where T is the average daily temperature at 2 m height (°C); G is the soil heat flux in MJ m^2 d^{-1}; Δ is the slope of the saturation vapor pressure-temperature relationship in kPa (°C)$^{-1}$; γ is the psychometric constant in kPa°C^{-1} and U_2 is the daily wind speed at 2 m height in m s^{-1}. Additionally, the calibrated FAO Penman-Monteith equation was used by a local calibrated coefficient in Eq. (2) according to the study of Razzaghi and Sepaskhah (2012).

The equation for reference evapotranspiration (ET$_o$, mm d^{-1}) by FAO-Penman method (Doorenbos and Pruitt, 1977) is as follows:

$$ET_o = C\ [0.408 \times W \times R_n + 0.27(1-W)F_u(e_s - e_a)] \tag{3}$$

where C is the correction coefficient; W is the coefficient that is dependent on air temperature; R_n is the net radiation (MJ m^{-2} d^{-1}); F_u is the function of wind speed; e_s is the saturated vapour pressure in kPa and e_a is the actual vapour pressure in kPa.

The equation for reference evapotranspiration (ET_o, mm d^{-1}) by Hargreaves-Samani method (Hargreaves and Samani, 1985) is as follows:

$$ET_o = 0.408 \times 0.0026 \times R_a \times (T_m + 17.8)(T_{\max} - T_{\min}) \tag{4}$$

where T_{max} is the maximum daily temperature in ^{o}C; T_{min} is the minimum daily temperature in ^{o}C and R_a is the extraterrestrial radiation in MJ m^{-2} d^{-1}.

Standard crop evapotranspiration

Standard crop evapotranspiration of safflower (ET_c) was calculated by multiplying reference evapotranspiration (ET_o) and crop coefficient (K_c) by Eq. (5) (Allen et al., 1998):

$$ET_c = K_c \times ET_o \tag{5}$$

Meanwhile, the safflower K_c was calculated according to Eq. (6) that was derived by a polynomial regression thorough the field measured data in full irrigation treatments from the second year of study.

$$K_c = a_0 + a_1\,(GDD) + a_2\,(GDD)^2 \tag{6}$$

where K_c is the crop coefficient as function of cumulative growing degree days (GDD, ^{o}C) and a_0, a_1 and a_2 are the constants. The coefficients were obtained for different treatments are given in Table 2, where N_a, N_b and N_c are the range of available soil nitrogen (fertilization + initial soil N + irrigation water) as $N<200$, $200<N<245$ and $N>245$ kg ha^{-1}, respectively.

In addition, the GDD was determined using Eq. (7) in which T_{max} and T_{min} are the maximum and minimum daily air temperature in °C, respectively; and T_b is the crop base temperature that is assumed as 5 °C for safflower (Mundel, 2004).

$$GDD = \sum\left(\frac{T_{max}+T_{min}}{2} - T_b\right) \tag{7}$$

Table 2. Coefficients of regression equation [Eq. (6)] for determination of crop coefficient of safflower under different planting methods and available soil nitrogen.

	N_a*	N_b	N_c	N_a	N_b	N_c
	On-ridge planting			In-furrow planting		
a_0	0.467748	0.387590	0.525981	0.550309	0.411414	0.441383
a_1	0.0010392	0.00147947	0.00120463	0.00096228	0.0011156	0.00131723
a_2	-0.00000039	-0.00000055	-0.00000046	-0.00000038	-0.00000039	-0.00000047

(*) N_a, N_b and N_c are the range of available soil nitrogen (fertilization+initial soil N+irrigation water) as $N<200$, $200<N<245$ and $N>245$ kg ha^{-1}, respectively.

Actual crop evapotranspiration

Since, under soil water stress conditions, the actual crop evapotranspiration (ET_a) is not further equal to ET_c; therefore, ET_a was calculated as follows (Allen et al., 1998):

$$ET_a = K_s \times ET_c \tag{8}$$

where K_s is the dimensionless coefficient for the soil water stress that varies between 0 and 1. The K_s values depends on the soil total available water in the root zone (TAW, mm), the soil water depletion in the root zone (D_r, mm) and the fraction of *TAW* that can be depleted from the root zone without impact of water stress on crop (p) according to Eq. (9) (Allen et al., 1998). In certain conditions of no water stress, K_s is higher than 1.0, which physically means no water stress and it should be taken as 1.0 whereas, K_s value approaches to 0 under water stress conditions.

$$K_s = \frac{TAW - D_r}{(1-p)TAW} \tag{9}$$

$$p = p_t + 0.04\ (5 - ET_c) \tag{10}$$

where p_t is the depletion fraction at ET_c of 5 mm d^{-1} that is considered as 0.60 for safflower (Allen et al., 1998).

Soil water depletion in the root zone at the end of each day was also determined using soil water balance as follows:

$$D_{r,i} = D_{r,i-1} - P_i - Eff\,(I_i) + RO_i - CR_i + ET_{a,i} + Dp_i \tag{11}$$

where $D_{r,i}$ is the depleted soil water depth from the root zone in day i (mm), $D_{r,i-1}$ is the depleted soil water depth in the root zone at the end of previous day $i-1$ (mm), P_i, I_i, RO_i and CR_i are the precipitation, irrigation depth, soil surface runoff and capillary rise from groundwater in day i (mm), $ET_{a,i}$ is the daily actual crop evapotranspiration (mm), Dp_i is the deep percolation to below the root zone in day i (mm), *Eff* is the irrigation efficiency considered for water loss through the soil pores and cracks that inhibit all irrigation water be accessible for crop. The soil surface runoff and capillary rise from groundwater did not consider in the lysimeters.

In order to begin the soil water balance calculation, the initial depleted soil water depth ($D_{r,i-1}$) was estimated using the following equation:

$$D_{r,i-1} = 1000 \times (\theta_{FC} - \theta_{i-1}) \times Z_r \tag{12}$$

where θ_{FC} is the volumetric soil water content at field capacity (cm^3 cm^{-3}), θ_{i-1} is the mean volumetric soil water content in the root zone at previous day $i-1$ (cm^3 cm^{-3}) and Z_r is the root depth (m).

The value of Dp_i after irrigation or a heavy rain was estimated by the following equation:

$$Dp_i = P_i + Eff\,(I_i) - ET_a - Dr_{,i-1} \tag{13}$$

In Eq. (13), it is assumed that the soil water content reaches field capacity at the wetting day; therefore, the $Dr_{,i}$ in Eq. (11) becomes zero.

In this model root depth was divided into four layers with same thickness but with different water absorption as 40%, 30%, 20% and 10% of actual evapotranspiration. Indeed, each value is associated with a quarter of the soil depth from the top. Root depth in each day of growing season was estimated by the following equation (Borg and Grimes, 1986):

$$Z_r = R_{d-\min} + R_{d-\max}(0.5 + 0.5\sin(3.03\frac{D_{ag}}{D_{tm}} - 1.47)) \tag{14}$$

where Z_r is the root depth (cm), R_{d-min} is the planting depth (cm) which is usually 4 cm for safflower, R_{d-max} is the maximum root depth, D_{ag} is the number of days after first irrigation, D_{tm} is the number of days after first irrigation that root reaches the maximum depth that was about 225 days in this study. When D_{tm} is not available, model consider 75% of the total growing season as D_{tm}.

The soil water content (SWC) was simulated for each quarter of root zone depth during the growing season from top to the bottom. Whereas, the soil water content was measured in four depths of soil profile; therefore, the predicted and measured values of soil water content were compared together after safflower root reached its maximum depth when it was equal to the soil depth. Then, the soil water contents at different layers were averaged in the root zone and compared with the average of predicted values.

Yields estimation

Similar to the procedure used in study of Bagheri et al. (2014), the daily LAI was derived from the measured data using the following empirical equation:

$$LAI = a_L \times \left\{1 - \exp\left[-(\frac{ET_a}{b_L})^3\right]\right\} \tag{15}$$

$$a_L = a_1 N + a_2 \tag{16}$$

$$b_L = b_1 N + b_2 \tag{17}$$

where N is the soil available nitrogen (kg ha^{-1}) that is provided by fertilization, irrigation water and initial soil N content; ET_a is the actual evapotranspiration using Eq. (8) and a_1, a_2, b_1 and b_2 are constants according to Table. 3. These constants were determined from the relationship between measured LAI and ET_a in the second year of experiment introduced as the parameterization stage. In this respect, Excel software was used to determine the relationship between parameters and finding the best fitted curves as parameterization stage. Afterward, the equations with its parameterized constants were used to simulate the crop parameters in validation stage.

In order to determine the soil evaporation, a relationship [Eq. (18)] was initially derived between the ratio of evaporation (E) to ET_a and LAI from the day of planting to the day that LAI_{max} is obtained.

$$\frac{E}{ET_a} = 1 - \left(\frac{d \times LAI}{g + LAI}\right) \qquad \text{(for LAI} \leq \text{LAI}_{max}\text{)} \qquad (18)$$

Afterward, the ratio of E/ET_a from the day of LAI_{max} to the harvest day was determined using the following exponential relationship:

$$\frac{E}{ET_a} = r \times \exp(s.LAI) \qquad \text{(for LAI} > \text{LAI}_{max}\text{)} \qquad (19)$$

where, *d*, *g*, *s* and *r* are the parameterized constants according to Table 3 which were obtained through the relationships of related data in the parameterization year.

Finally, soil evaporation was determined according to Eq. (20) and the crop transpiration was calculated by subtracting the determined evaporation from ET_a [Eq. (21)].

$$E = \left(\frac{E}{ET_a}\right) ET_a \qquad (20)$$

$$T = ET_a - E \qquad (21)$$

The biomass production (Y_t) was determined using transpiration (T) and the vapor pressure deficit (e_s-e_a) as follows (Arkley, 1963):

$$Y_{t,i} = f.\left[\frac{T}{e_s - e_a}\right] \qquad (22)$$

where $Y_{t,i}$ is the daily biomass production in kg ha^{-1}, T is the transpiration rate in mm d^{-1}, e_s is the saturated vapor pressure in kPa, e_a is the actual vapor pressure in kPa and f is the constant (shown in Table 3). The seasonal biomass production (Y_t) was calculated by summation of daily $Y_{t,i}$.

The harvest index (HI) of safflower was determined using Eq. (23) in which T_{cum} is the seasonal transpiration in mm and k is a constant as shown in Table 3.

$$HI = k\sqrt{T_{cum}} \qquad (23)$$

Finally, safflower seed yield (Y in kg ha^{-1}) was calculated as follows:

$$Y = HI \times \sum Y_{t,i} \qquad (24)$$

Table 3. The parameterized coefficients of regression models.

Equation	parameterized coefficient		I_1 P_1	I_1 P_2	I_2 P_1	I_2 P_2
$LAI = a_L \times \left\{ 1 - \exp\left[-(\frac{ET_a}{b_L})^3 \right] \right\}$	a_L	a_1	0.012	0.020	0.072	0.129
		a_2	3.266	2.020	-5.877	-17.446
	b_L	b_1	0.688	0.688	3.257	3.257
		b_2	691.8	691.8	202.6	202.6
$\frac{E}{ET_a} = 1 - (\frac{d \times LAI}{g + LAI})$	D		1.078	1.109	1.132	1.136
	G		0.292	0.388	0.402	0.418
$\frac{E}{ET_a} = r \times \exp(s.LAI)$	R		0.2628	0.2294	0.1859	0.1549
	S		-0.464	-0.477	-0.617	-0.686
$Y_t = f.\left[\frac{T}{e_s - e_a} \right]$	F		17.655	21.605	17.655	21.605
$HI = k\sqrt{T_{cum}}$	K		0.00782	0.00782	0.00782	0.00782

Model overview

The model flowchart is shown in Figure 2. This model was programmed in C# language that is described by the following sections:

Inputs to the safflower model

The safflower model has three input files including climate.xls, irrigation.xls and ETo.xls in Excel format in which the ETo.xls is necessary only if the ET_o is inserted by user. The ET_o may be determined by methods of Penman-Monteith, calibrated Penman-Monteith, FAO-Penman, Hargreaves-Samani or directly inserted by user. The meteorological information in climate.xls file including the days after first irrigation (DAFI), maximum and minimum daily temperature (°C), maximum and minimum relative humidity (%), wind speed (m s^{-1}), sunshine hours (hr), precipitation (mm) and the Julian day according to the planting date. Furthermore, the irrigation and ET_o files contain the daily irrigation depths (mm) and ET_o (mm day^{-1}), respectively. Additionally, there are some variables that are input manually by the user consisting of geographical parameters (elevation from sea level, latitude), soil characteristics (initial soil water content, soil water contents at FC, PWP), irrigation efficiency (%) and available soil nitrogen (kg ha^{-1}). Meanwhile, the method of planting and irrigation regime are separately chosen by user.

Outputs from the safflower model

The model outputs are created in four Excel files that are Evapotranspiration.xls, Growth.xls, SoilMoisture.xls and Yields.xls. The details in these files are presented in Table 4.

Table 4. Characteristics of output results created by safflower model.

Output file	Column name	Unit	Description
Evapotranspiration.xls			
	DAFI	days	days after first irrigation
	ET_o	mm d^{-1}	daily ET_o through the option that may be chosen by user
	ET_c	mm d^{-1}	daily standard evapotranspiration for safflower
	ET_a	mm d^{-1}	daily actual evapotranspiration for safflower
	E	mm d^{-1}	daily soil evaporation
	T	mm d^{-1}	daily safflower transpiration
	K_c	-	daily crop coefficient (K_c)
	GDD	^oC	cumulative growing degree days
Growth.xls			
	DAFI	days	days after first irrigation
	LAI	-	daily leaf area index
	Z_r	cm	daily safflower root depth in growing season
SoilMoisture.xls			
	DAFI	days	days after first irrigation
	Teta1	$cm^3 cm^{-3}$	daily soil water content in the first quarter of root zone
	Teta2	$cm^3 cm^{-3}$	daily soil water content in the second quarter of root zone
	Teta3	$cm^3 cm^{-3}$	daily soil water content in the third quarter of root zone
	Teta4	$cm^3 cm^{-3}$	daily soil water content in the fourth quarter of root zone
	TetaAve	$cm^3 cm^{-3}$	daily average of soil water content in the root zone
	K_s	-	daily soil water stress coefficient in the root zone
	P	-	daily actual coefficient of readily available water in the root zone.
Yields.xls			
	DAFI	days	days after first irrigation
	Biomass	kg ha^{-1}	daily biomass of safflower (straw+seed)
	Total Biomass	kg ha^{-1}	seasonal biomass of safflower,
	Seed Yield	kg ha^{-1}	seasonal seed yield produced by safflower
	Straw Yield	kg ha^{-1}	seasonal straw produced by safflower

Model performance evaluation

In this study, we investigated the outputs of safflower model, including the evapotranspiration, transpiration, soil surface evaporation, biomass, seed yield, straw yield, LAI and soil water content. The data obtained in the second year of study was used to parameterize the model and then validated by the first year observations. To find out the level of agreement between the model simulation outputs and field measured data, the following statistical indices were used.

$$NRMSE = \frac{[1/n\sum_{i=1}^{n}(X_i - Y_i)^2]^{0.5}}{O} \quad (22)$$

$$d = 1 - \left\{ \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=1}^{n}(|X_i - O| + |Y_i - O_e|)^2} \right\} \quad (23)$$

where *NRMSE* and *d* is the normalized root mean square error and the index of agreement, respectively; and *n* is the number of observations, *X* is the measured values, *Y* is the predicted values, *O* is mean values of the measured data and O_e is mean value of the predicted data. The value of *NRMSE* and *d* approaches 0.0 and 1.0, respectively, for accurate simulation. The closer the *NRMSE* is to 0, the model is more accurate. The value of *d* varies between 0 and 1.0 and the closer its value to 1.0, the model accuracy is higher. In addition, relationship between the measured and predicted values was compared with 1:1 line, statistically.

Results and Discussions

Model parameterization

Actual evapotranspiration

Considering the different reference evapotranspiration equations, the calibrated Penman-Monteith equation (Razzaghi and Sepaskhah, 2012) was used to estimate the daily ET_0. The relationship between the predicted and measured values of seasonal ET_a, for model development in the second year is presented in Figure 3(a_1). In order to fit the best relationships between the measured and predicted values, the slopes and intercepts of the linear relationships were analyzed statistically (Table 5). For the model development stage (parameterization), the intercept was not significant for ET_a relationship; therefore, the regression equation was forced to pass the origin of coordinates. The maximum seasonal value of the measured ET_a was 1419 mm for the parameterization stage; whereas, the predicted value was 1393 mm, that they were similar. Besides, minimum value of the measured ET_a determined as 1114 mm for the parameterization stage which were close to the minimum values of predictions as 1082 mm. According to Figure 4, daily variation of predicted ET_a matched well with the measurements during the growing season. The value of *NRMSE* and agreement index (d) for seasonal ET_a were 0.035 and 0.96 in parameterization year, respectively. Consequently, safflower model could predict the actual evapotranspiration very accurately in this stage.

Soil evaporation

The relationship between the predicted and measured values of seasonal soil evaporation (E), for model development is shown in Figure 3(a_2). For the model development stage (parameterization), the intercept was not significant for E relationship; therefore, the regression equation was forced to pass the origin of coordinates (Table 5). The maximum value of the measured seasonal E for parameterization stage was 339 mm and the corresponding predicted value reached 334 mm which are very close to each other. Moreover, the minimum value of measured E was obtained as 275 mm for the parameterization period that was close to the minimum predicted value as 283. Based on Figure 4, daily variation of predicted evaporation rates corresponded to the measurements in a good manner during the growing season. Furthermore, the values of *NRMSE* and *d* for seasonal soil E were 0.033 and 0.92, respectively. Therefore, the accuracy of estimated seasonal evaporation (E) was good and their results were close to the measured E values at parameterization stage.

Transpiration

Relationship between the predicted and measured values of seasonal transpiration (T), for model development stage is presented in Figure 3(a_3). Considering the statistical analysis of equation between the measured and predicted T values, the intercept was not significant for T relationship; therefore, the regression equation between the predicted and measured values was forced to pass the origin of coordinates (Table 5). Comparably, the maximum value of the measured seasonal T was 1078 mm and it was predicted as 1080 mm for the parameterization step; thus, they are completely matched with each other. On the other hand, the minimum value of measured T was 814 mm at parameterization that is close to the minimum value of predictions as 783 mm. The predicted and measured rates of transpiration at daily scale were shown in Figure 4 with a fine accordance to each other. With respect to the seasonal safflower transpiration (T), the value of *NRMSE* and *d* were 0.044 and 0.95 for the parameterization, respectively. Therefore, safflower model estimated the seasonal transpiration with high accuracy.

Leaf area index (LAI)

Results of safflower model for daily prediction of LAI in two samples of extreme and least treatments indicated a fair agreement with the measured daily values, especially in OFI (Figure 5). The relationship between the predicted and measured LAI were presented in Figure 6(a_1) for different treatments. Since, the intercept of equations was not significant, the regression equation between the predicted and measured LAI values was forced to pass the origin of coordinates (Table 5). The values of *NRMSE* and *d* for model development stage (parameterization) are 0.27 and 0.97, respectively that showed a fair prediction of LAI by the safflower model in parameterization.

Soil water content

Model output for daily prediction of soil water content (SWC) against the measured values (Figure 5) indicated an acceptable agreement, especially in OFI treatments. The relationship between the measured and predicted mean soil water content was determined by a linear regression analysis [Figure 6(a_2)] including three times of the soil water measurements.

At the stage of model development (parameterization), the values of *NRMSE* and *d* were 0.11 and 0.64, respectively. Besides, the statistical analysis indicated an acceptable estimation of soil water content by the proposed model, although it was accompanied by some overestimating of soil water content in comparison with the measured values. Similar observations were obtained by Yarami and Sepaskhah (2016) in which the discrepancy of results were due to the probable measurement error by neutron scattering method. On the other hand, the alternate furrow irrigation was applied in this experiment as a deficit irrigation strategy in which irrigation water is applied in alternate furrows. Considering the water balance method for prediction of soil water content, VAFI strategy may perform differently from the ordinary deficit irrigation techniques in which irrigation water is distributed uniformly in soil.

Yields production

Relationship between the predicted and measured values of safflower biomass, seed yield and straw were presented in Figure 7, for model development stage (parameterization). Regarding to the statistical analysis, the intercept of equation was not significant for biomass, seed yield and straw at model development stage (parameterization); therefore, the regression equation was forced to pass the origin of coordinates (Table 5). The values of *NRMSE* and *d* for biomass simulation were 0.21 and 0.66 for parameterization, respectively. These statistical parameters indicated that the accuracy of estimated safflower biomass was generally acceptable and their results were close to the measured biomass values. However, a minor underestimation was observed in comparison with the measured values. This issue may have been resulted from the parameterized coefficient (f) in Eq. (22) in which a constant value was determined for this coefficient in different growing stages of safflower. In order to evaluate the predicted safflower seed yield at model development stage, the values of *NRMSE* and *d* were 0.22 and 0.69, respectively. Therefore, the safflower seed yield was predicted in an acceptable manner at parameterization stage; accompanying by a negligible underestimation compared with the measured values. With respect to the estimations of safflower straw at parameterization, the values of *NRMSE* and *d* were 0.21 and 0.64, respectively. These statistical parameters indicated that the model could estimate the safflower straw yield with acceptable accuracy and this result is close to the measured values.

Model validation

Actual evapotranspiration

For validation of model for ET_a, the intercept of equation between the predicted and measured values of seasonal ET_a was significant (Table 6). In addition, the value of *NRMSE* and *d* for seasonal ET_a were 0.035 and 0.90 for validation stage, respectively [Figure 3(b_1)]. These statistical parameters indicated that the accuracy of estimated seasonal actual evapotranspiration was good and their results were close to the measured ET_a values. However, a tendency for under-prediction of ET_a observed in VAFI treatments that may be attributed to the non-uniform distribution of soil water in

VAFI lysimeters and the difficulties that is associated with pointwise measurement of soil water content. In analogy, the maximum seasonal value of the measured ET_a was 1210 mm for validation stage and the corresponding predicted value was 1230 mm that were close to each other. Furthermore, minimum value of the measured ET_a was 1054 mm for validation that was close to the predicted minimum value as 1000 mm. Moreover, the daily variation of predicted ET_a agreed finely with the measured values as shown in Figure 8. Consequently, the safflower model was capable to predict the seasonal actual evapotranspiration fairly well for both years of model development and validation.

Evaporation

Based on Table 6, the intercept of equation between the predicted and measured E values was significant in validation. Additionally, the value of *NRMSE* and *d* for seasonal soil E were 0.076 and 0.64, respectively [Figure 3(b_2)]. These statistical parameters indicated that the accuracy of estimated seasonal evaporation (E) is relatively fine and accompanied by acceptable discrepancies compared with the measured E values. Considering the results, the maximum value of the measured seasonal E was 311 mm for the validation year and the predicted value was 321 mm that is very close to each other. In addition, the minimum value of measured E was determined as 241 mm at validation, that was similar to the minimum value of predictions as 268 mm. Based on Figure 8, the predicted rates of evaporation at daily scale were acceptable in accordance with the measurements during the growing season. Therefore, the safflower model was capable to predict the soil evaporation with good accuracy for model validation stage.

Transpiration

The value of *NRMSE* and *d* are 0.07 and 0.71 for the validation, respectively. These statistical parameters indicated that the accuracy of estimated seasonal transpiration is good and their results are close to the measured values [Figure 3(b_3)]. Comparably, the maximum value of the measured seasonal T was 936 mm for validation step while it was predicted as 915 mm, that are very close to each other. Furthermore, the minimum value of measured T was 784 mm at validation phase, in which the minimum predicted values closely obtained as 705 mm. The predicted rates of daily transpiration were finely in accordance with the measured values (Figure 8). Accordingly, the safflower model is capable to predict the seasonal transpiration of safflower fairly well for validation year.

Leaf area index (LAI)

In the validation stage of predicted LAI, the values of *NRMSE* and *d* are 0.56 and 0.92, respectively [Figure 6(b_1)]. Although, the value of *d* showed an accurate estimation of LAI with acceptable values, but the high value of *NRMSE* indicated that predicted LAI values for validation stage is not acceptable. On the other hand, the prediction of safflower model for daily LAI indicated a good agreement with the measured daily values in OFI, however it was not fair for VAFI treatment (Figure 9). Indeed, the safflower model overestimated LAI when it reached the values of LAI_{max} at late season almost in VAFI treatments. Similar findings about the LAI prediction by Eq. (15) reported in studies of Sepaskhah et al. (2013) and Yarami and Sepaskhah (2016) on saffron and Bagheri et al. (2014) on maize. They pointed out this equation may not be appropriate for LAI modelling in all growth stage of crop and it may act differently in various environmental conditions due to probable uncertainty in the relationship between LAI and ET_a. Moreover, the delay for planting of safflower in the validation year of our study and also shortening of growing season, caused LAI to be reduced and not having sufficient leisure to reach the favorable LAI values in comparison with the parameterization year. This issue may also justify the poor estimation of LAI at validation stage.

Soil water content

For validation stage [Figure 6(b_2)], the values of *NRMSE* and *d* were 0.14 and 0.51 between the predicted and measured values of soil water content, respectively. The statistical analysis showed that prediction of soil water content in validation stage is in a lower accuracy than the model development stage. Indeed, the soil water content mostly overestimated by the proposed model and they were almost related to the in-furrow planting treatments. However, the predicted values of soil water content can be acceptable due to low value of *NRMSE*. Furthermore, the daily simulated SWC against the measured values (Figure 9) indicated an acceptable agreement, especially for OFI treatment; however, some discrepancies are observed in VAFI treatments at the end of growing season.

Yields production

The statistical analysis of yields prediction at validation stage was presented in Table 6. The intercept of equations between the predicted and measured values of safflower biomass, seed yield and straw was significant at validation. For this stage, the values of *NRMSE* and *d* for biomass simulation were 0.12 and 0.80, respectively. These statistical parameters indicated that the accuracy of estimated safflower biomass is good and their results were close to the measured biomass values. In this respect, the results of validation showed also higher accuracy in estimation than the model development stage (Tables 5 and 6) that may be attributed to the better data fitting in validation stage. Furthermore, the values of *NRMSE* and *d* for seed yield simulation were determined as 0.16 and 0.70 for validation, respectively. Therefore, a good simulation on safflower seed yield was obtained by the safflower model and results were acceptably close to the measured value. Similarly, the predicted results in validation were more close to the measured values compared with the model development stage. Regarding to the straw simulation, the values of *NRMSE* and *d* for validation were 0.11 and 0.82, respectively. The statistical analysis showed that estimation on safflower straw yield was accurate with close results to the measured values. Generally, safflower model was applicable to determine safflower yield components and it could be a valuable tool for farm management under different irrigation strategies, planting methods and nitrogen fertilization rates.

Table 5. Relationship between the predicted and measured actual evapotranspiration (ET), evaporation (E), transpiration (T), soil water content (θ), leaf area index (LAI), biomass yield, seed yield and straw (DM) yield for parameterization stage.

Parameter	Equation	Coefficient of determination	P_{value}	NRMSE	d	Slope	Intercept
Evapotranspiration	$ET_p = 0.995 (ET_m)$	0.84	2×10^{-5}	0.035	0.96	S	NS
Soil surface evaporation	$E_p = 1.016 (E_m)$	0.73	1×10^{-4}	0.033	0.92	S	NS
Transpiration	$T_p = 0.986 (T_m)$	0.84	3×10^{-5}	0.044	0.95	S	NS
Leaf area index (LAI)	$LAI_p = 0.858 (LAI_m)$	0.97	9×10^{-111}	0.27	0.97	S	NS
Soil water content	$\theta_p = 0.789 (\theta_m) + 6.738$	0.59	5×10^{-8}	0.11	0.64	S	S
Biomass	$BioM_p = 0.854 (BioM_m)$	0.51	3.7×10^{-3}	0.21	0.66	S	NS
Seed yield	$SeedY_p = 0.858 (SeedY_a)$	0.56	5.1×10^{-3}	0.22	0.69	S	NS
Straw dry matter	$SDM_p = 0.852 (SDM_m)$	0.43	4×10^{-3}	0.21	0.64	S	NS

Table 6. Relationship between the predicted and measured actual evapotranspiration (ET), evaporation (E), transpiration (T), soil water content (θ), leaf area index (LAI), biomass yield, seed yield and straw (DM) yield for validation stage.

Parameter	Equation	Coefficient of determination	P_{value}	NRMSE	d	Slope	Intercept
Evapotranspiration	$ET_p = 1.565 (ET_m) + 668.3$	0.89	5×10^{-6}	0.038	0.89	S	S
Soil surface evaporation	$E_p = 0.722 (E_m) + 96.09$	0.78	1×10^{-4}	0.076	0.64	S	S
Transpiration	$T_p = 0.952 (T_m)$	0.68	9×10^{-5}	0.07	0.71	S	NS
Leaf area index (LAI)	$LAI_p = 0.953 (LAI_m)$	0.75	3×10^{-48}	0.56	0.92	S	NS
Soil water content	$\theta_p = 0.602 (\theta_m) + 10.01$	0.45	2×10^{-6}	0.14	0.51	S	S
Biomass	$BioM_p=0.635(BioM_m) + 5207$	0.71	6×10^{-4}	0.12	0.81	S	S
Seed yield	$SeedY_p=0.782(SeedY_a)+934.2$	0.77	2×10^{-4}	0.16	0.72	S	S
Straw dry matter	$SDM_p=0.587(SDM_m)+4391.9$	0.66	1.2×10^{-3}	0.11	0.83	S	S

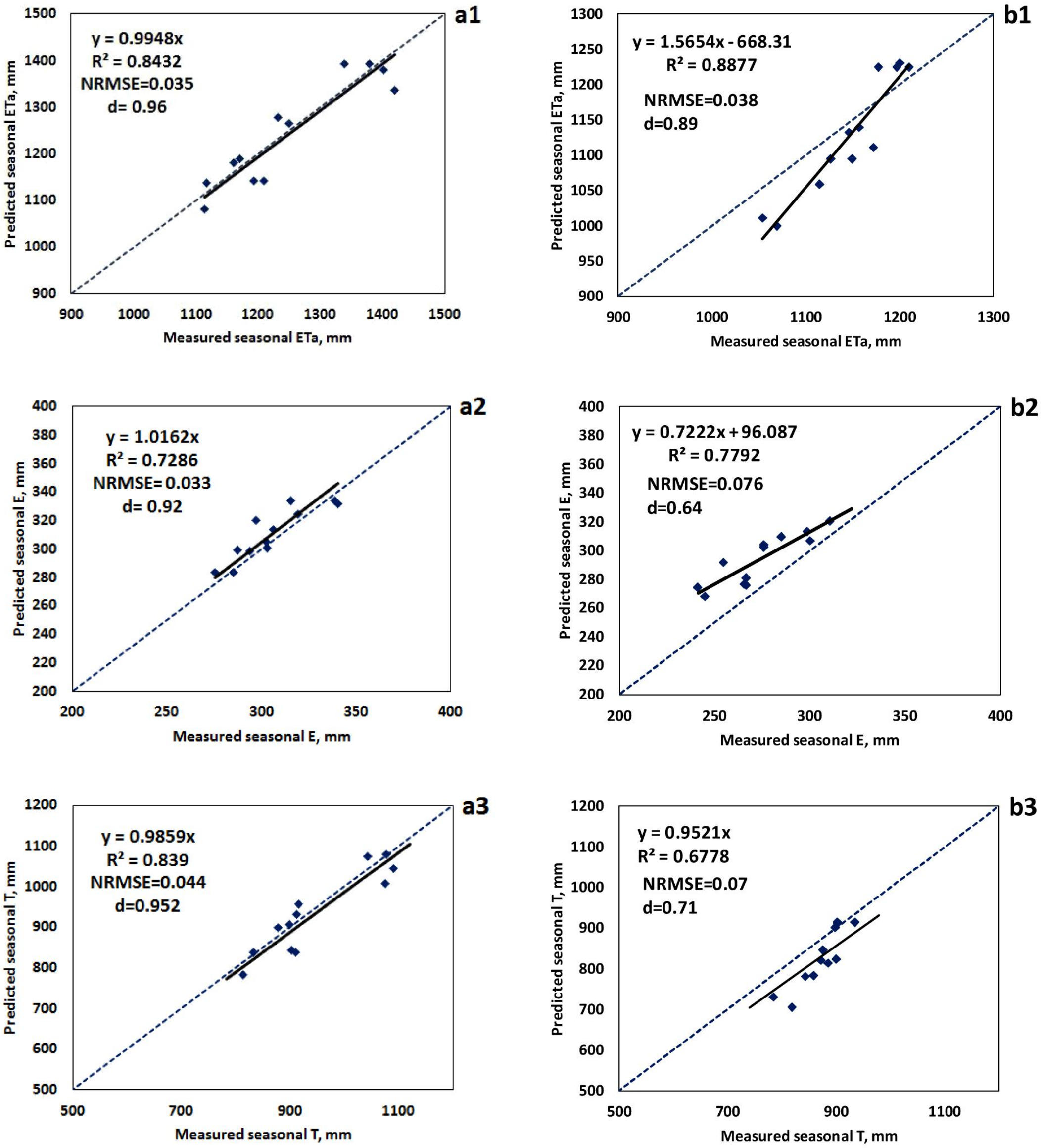

Figure 3. Relationship between the predicted and measured actual seasonal evapotranspiration (ET_a), soil evaporation (E) and transpiration. (a): parameterization; (b): validation stage.

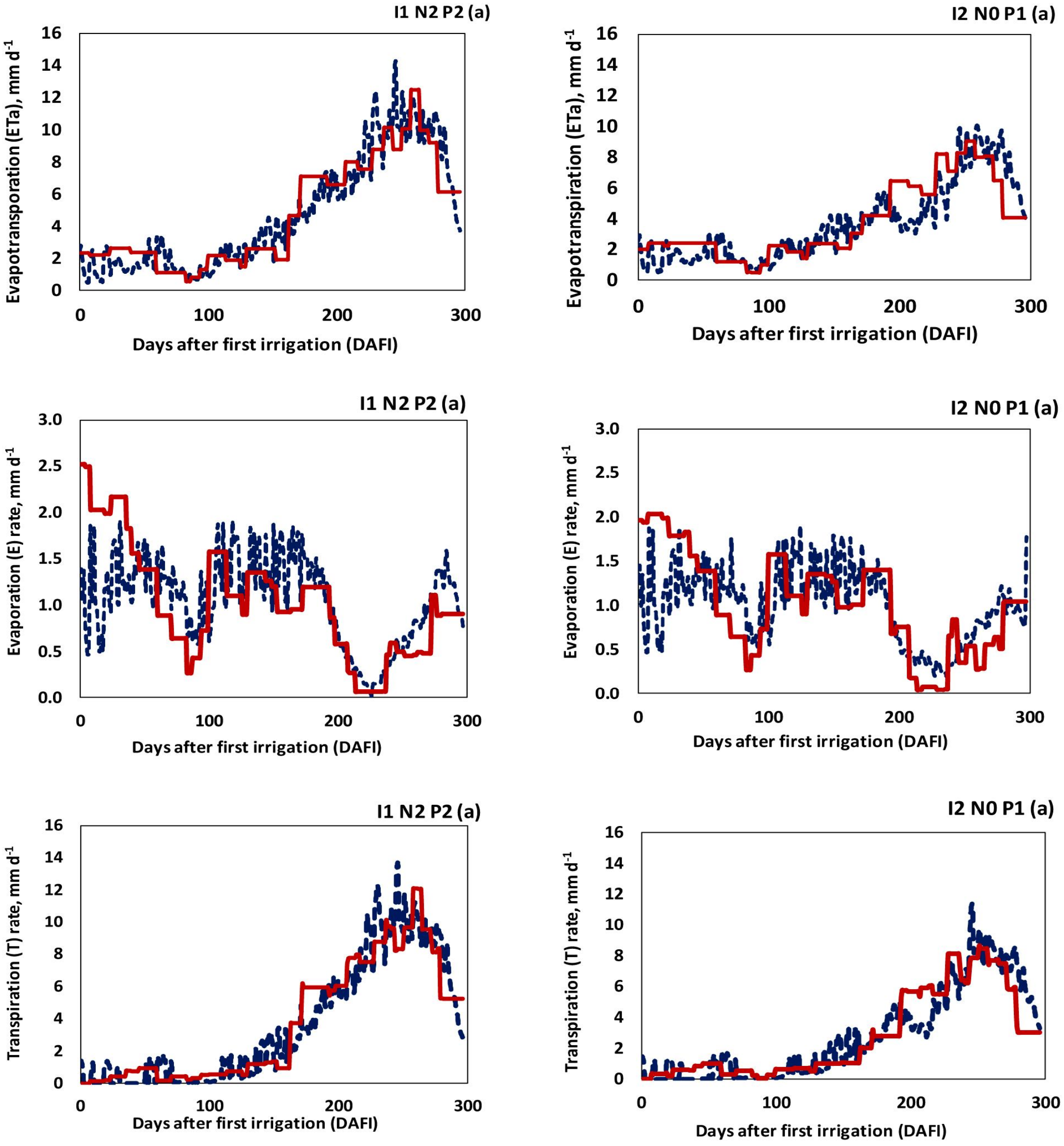

Figure 4. Daily variation of the measured and predicted ET_a, E and T in extreme and least treatments (parameterization). Predicted (----); Measured (—).

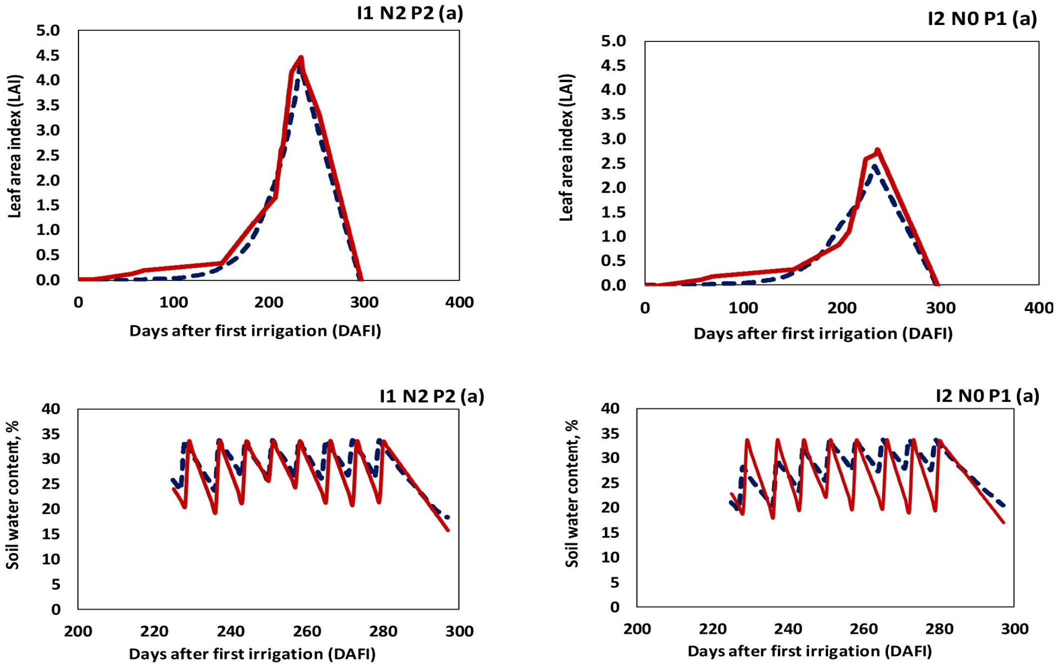

Figure 5. Daily variation of the measured and predicted LAI and soil water content in extreme and least treatments (parameterization). Predicted (----); Measured (—).

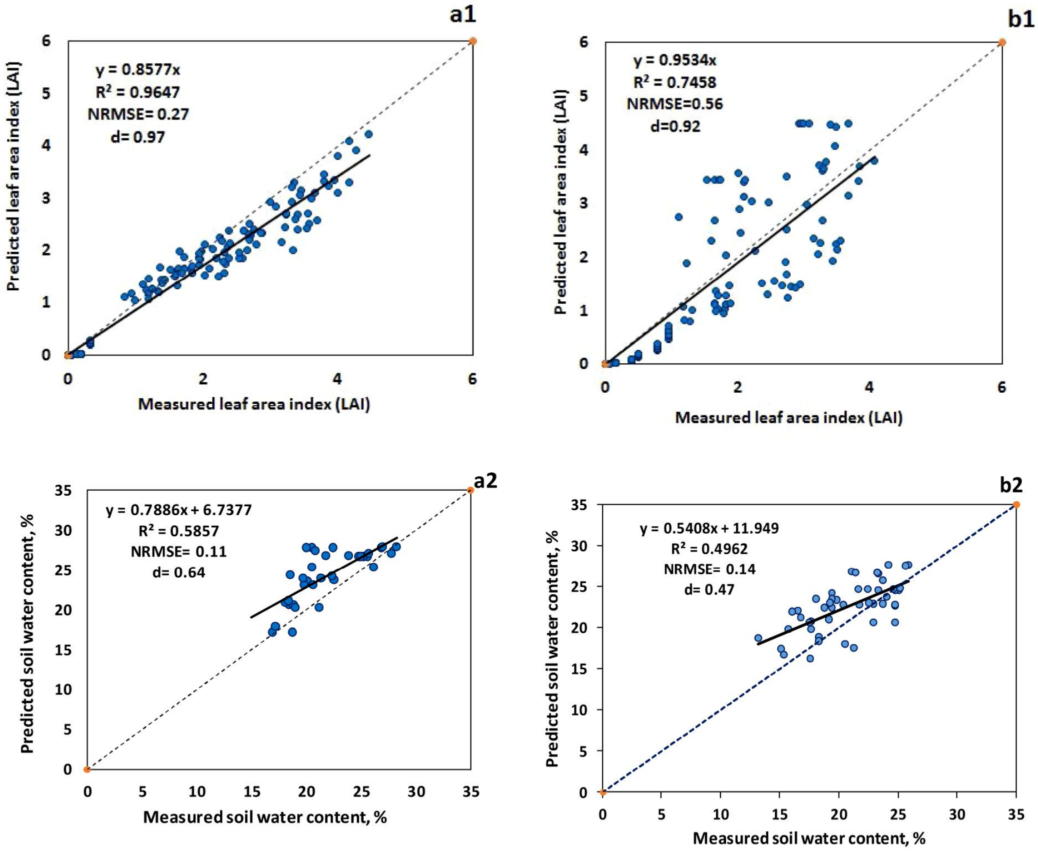

Figure 6. Relationship between the predicted and measured leaf area index (LAI) and soil water content, (a): parameterization; (b): validation stage.

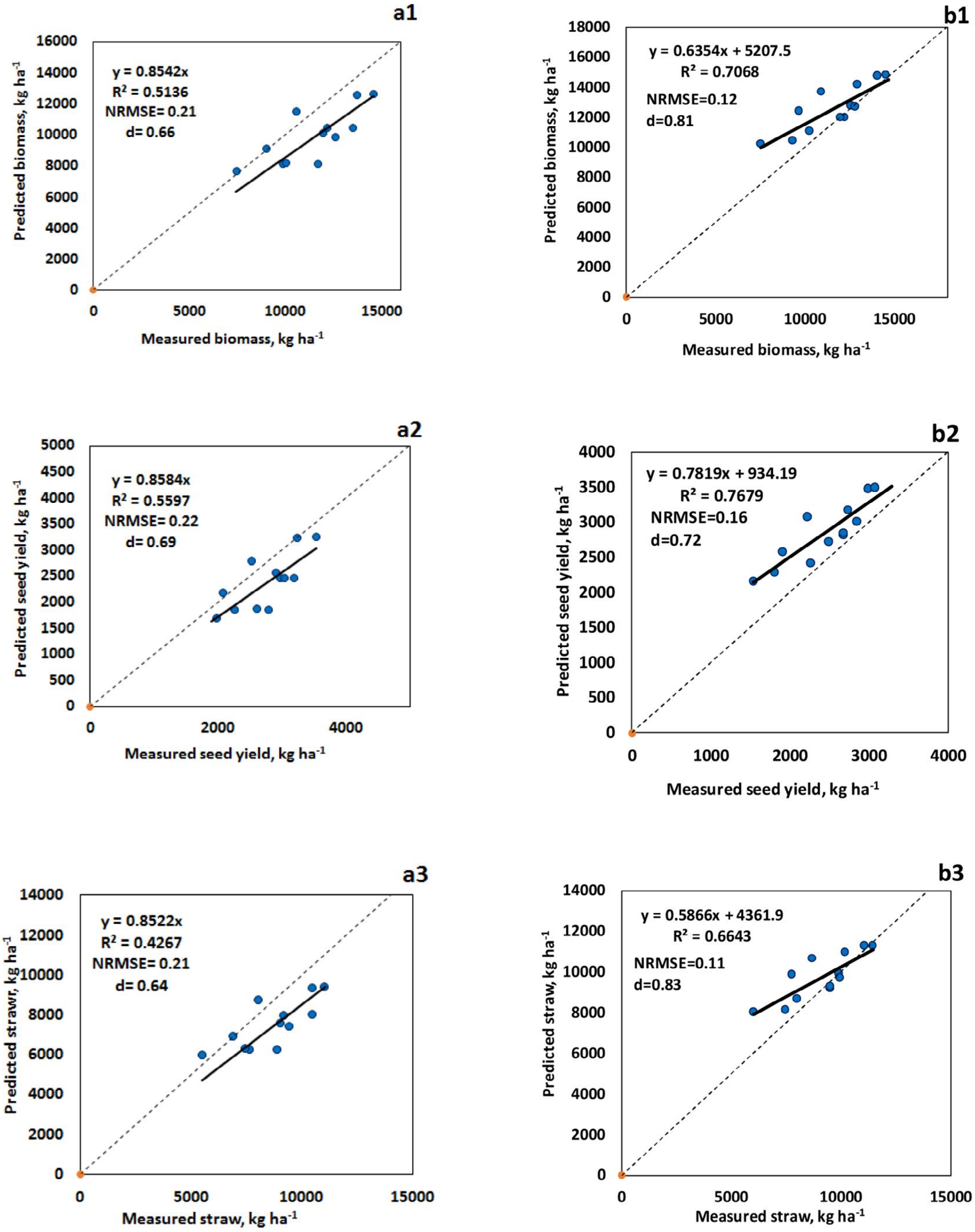

Figure 7. Relationship between the predicted and measured (1) biomass yield, (2) seed yield and (3) straw yield; (a): parameterization and (b): validation year.

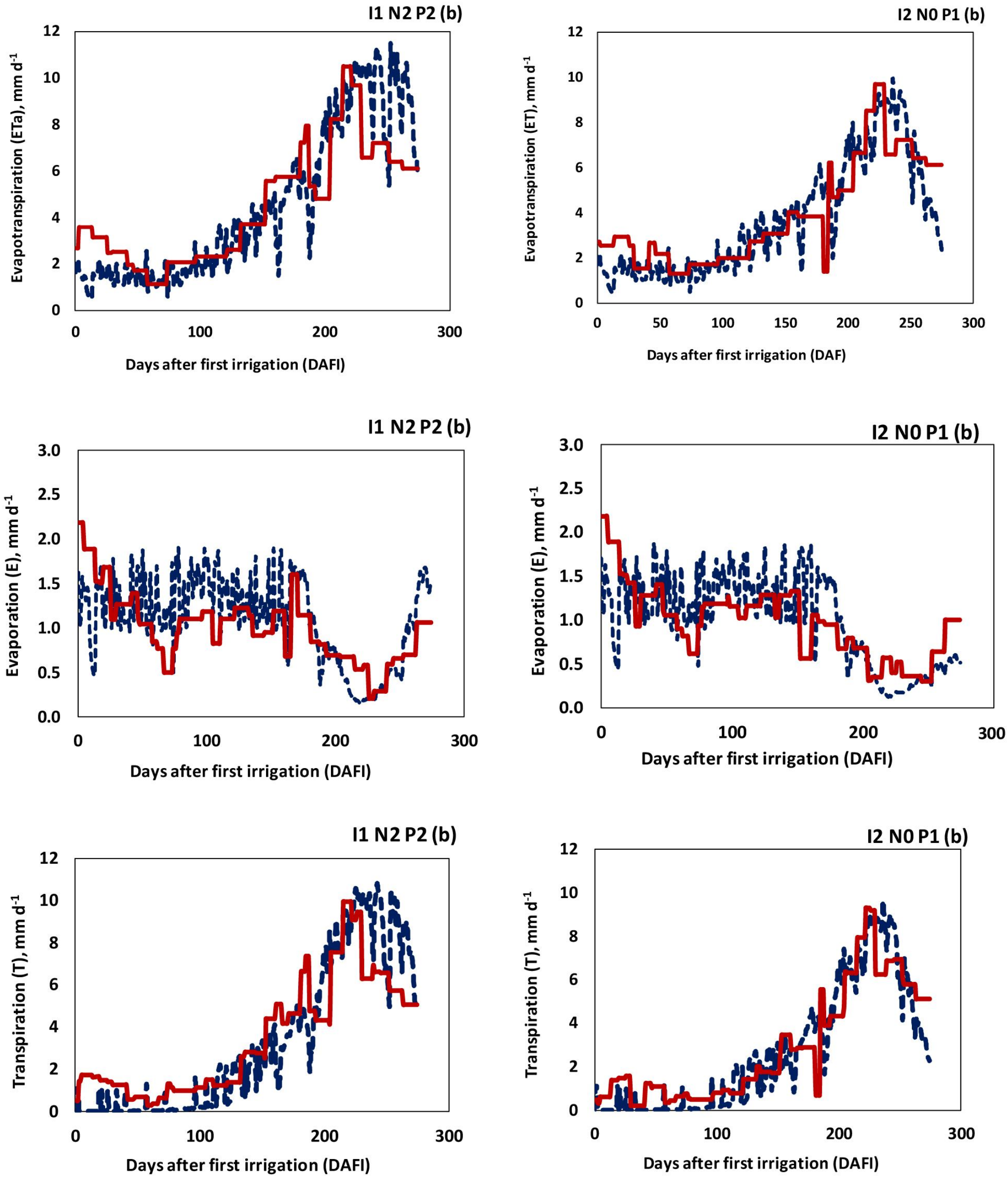

Figure 8. Daily variation of the measured and predicted ET_a, E and T in extreme and least treatments (validation). Predicted (----); Measured (──).

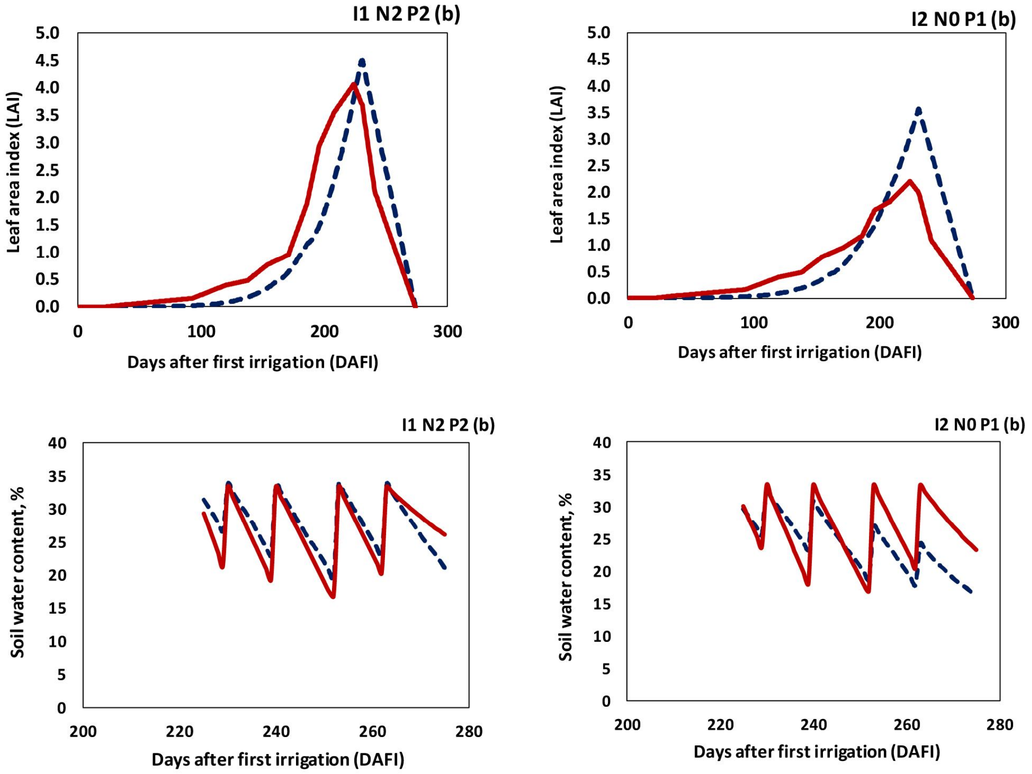

Figure 9. Daily variation of the measured and predicted LAI and soil water content in extreme and least treatments (validation). Predicted (----); Measured (—).

Conclusions

In this study, the Safflower Model was developed to predict the actual evapotranspiration, soil surface evaporation, transpiration, soil water content, leaf area index, biomass, seed yield and straw of safflower under different irrigation strategies, planting methods and nitrogen fertilization by using two years of field experimental data. This model is based on soil water balance and other simple plant physiological relationships; therefore, it needs a few data to be input in the model, therefore it is an effective tool for farm planners and decision makers. Meanwhile, various parameterized coefficients and options in the model may be adopted by the users; hence, safflower model can also be used in other areas and climate conditions. The results showed that safflower model estimated the actual evapotranspiration, crop transpiration, soil surface evaporation, LAI and yields of safflower with good accuracy at parameterization stage. Furthermore, these parameters were favorably predicted in validation stage; however, some discrepancies were observed about E and LAI in comparison with the measured data. With regard to the soil water budget used for estimation of soil water content in both irrigation regimes, the model approximately overestimated the soil water content in parameterization and validation. However, the predictions were still acceptable due to low values of NRMSE. Finally, safflower model can be a useful tool for prediction of growth and yield specifically in situations that field experiments are costly and not possible. This model can favorably help farmers for better farm management and decision makings.

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