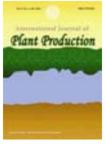

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Developing a dynamic yield and growth model for saffron under different irrigation regimes

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Abstract

Better irrigation management and more efficient management of crop production require modeling of plant growth and crop yield. More applicable models are usually simple and requires less and accessible inputs. The objective of this study was to develop a model for growth and yield prediction of saffron under various irrigation regimes. In this modeling soil water budget and other simple relationships for evapotranspiration partitioning, leaf area index determination and leaf dry matter-transpiration function, corm-transpiration function and saffron-corm function were used. The developed model was calibrated based on available data of basin irrigation experiment under different irrigation regimes and verified based on independent data under different climatic conditions. In calibration, the comparison between predicted and measured values of different crop parameters did not show any significant difference (P=0.05) and model was able to estimate LAI (with NRMSE=0.16), crop evapotranspiration (NRMSE=0.19), surface evaporation (NRMSE=0.22), leaf dry matter (NRMSE=0.33) and corm yield (NRMSE=0.19) and saffron yield (NRMSE=0.16) properly. In validation, the statistical results of comparison between predicted and measured values of various crop parameters were different and model was able to estimate corm and saffron yield with acceptable accuracy. Furthermore, this model might be used only for saffron crop because the incorporated crop functions are developed for saffron.

Keywords: Saffron modeling; Saffron yield; Total dry matter; Evapotranspiration; Leaf area index; Corm yield.

Introduction

Water is becoming the most important limiting factor for agricultural production especially in semi-arid and arid regions. Therefore, crops with low water requirements (i.e., saffron) are planted in these areas. Using proper irrigation methods and frequency for saffron are necessary for design of irrigation systems, irrigation scheduling and water resources planning. Eftekharzadeh-Maraghei (1994) studied the interaction effects of irrigation intervals (7 and 15 days) and nitrogen application rates (0 and 75 kg ha^{-1}) on saffron yield. Results showed that the irrigation interval of 15 days and nitrogen application rate of 75 kg ha^{-1} produced the highest yield. Alavi-Shahri (1995) used different amounts of irrigation water based on 45%, 65% and 85% evaporation from class A pan for irrigating saffron in combination with different levels of animal manure. Results showed that the amount of irrigation based on 85% of evaporation from class a pan resulted in the highest yield. Furthermore, Azizi-Zohan et al. (2009) studied the effect of three irrigation intervals (12, 24 and 36 days) plus rain-fed treatments on saffron yield in different years. Results showed the highest yield at 12-day irrigation interval in basin irrigation. As a winter crop, saffron irrigation scheduling is affected by rainfall in the growing season. Sepaskhah et al. (2008) indicated that the value of optimum applied irrigation water for saffron is most affected by seasonal rainfall and an equation was presented for water resources planning with deficit irrigation under different seasonal rainfall.

Apart from water, there are other several factors/variables such as soil condition, soil nutrition which have significant influence on crop growth. However, studying the mutual effects of all variables is not simple. To study the effect of different variables on crop growth and production, model applications are the best way.

Simulation of plant growth and crop yield became essential for better scheduling and more efficient management of crop production processes (Zand-Parsa et al., 2006). Several complex models have been developed for estimation of different crops yield, which they required a lot of measurements and often non accessible input data (Smith, 1992; Yin et al., 2000; Ziaei and Sepaskhah, 2003). As an example, Zand-Parsa et al. (2006) and Majnooni-Heris et al. (2011) simulated maize growth and grain yield for two irrigation systems (line source sprinkler and furrow irrigation, respectively) by using multi-component model which was quite complicated. Simple models which can estimate the crop yield are therefore an advantage and can be easily used for practical applications using simple equations and fewer input data. Pirmoradian and Sepaskhah (2006) developed a very simple model for simulation of rice grain and biomass yields by using maximum leaf area index, harvest index and light use efficiency. In other simple models, soil water budget and simple relationships for evapotranspiration partitioning, leaf area index and transpiration function was used to develop a simple model for growth and yield production of cowpea under soil water stress (Sepaskhah and Ilampour, 1996; Sepaskhah et al., 2006b) and for sugar beet, winter wheat and sweet maize under soil water and salt stress (Sepaskhah et al., 2006a). However, there is still a need for further study which considers different abiotic and biotic stresses. As mentioned above water is the main limiting factor for agricultural production (Cassman et al., 1997; Dagdelen et al., 2006) and using simple approach to model saffron yield under water stress conditions has not been studied yet.

Hence, the objective of this study was to use soil water budget and other simple relationships for evapotranspiration partitioning, leaf area index determination and harvest index-transpiration function to develop a dynamic crop growth model to simulate growth and yield prediction of saffron under various water application rates.

Materials and Methods

Model description

The developed model for simulation of saffron growth and other variables was programmed in C# language with a Graphical User Interface (GUI). The model structure has one main body and five sub-routines. Further, this model has one input file (in.mdb) and one output file (out.mdb) including: yield, LAI, ET_o, ET_c and Watercont. The schematic of this model is shown in Figure 1.

Model input file

The model has an input file of in.mdb with Access format and contains meteorological information such as minimum and maximum daily temperature, minimum and maximum relative humidity, wind speed, sunshine hours and precipitation amount. In addition Julian date was used to show the growing period. The model includes some variables (such as geographical parameters and soil water content at FC and PWP) which need to be modified for other regions and it has to be modified in the program by user.

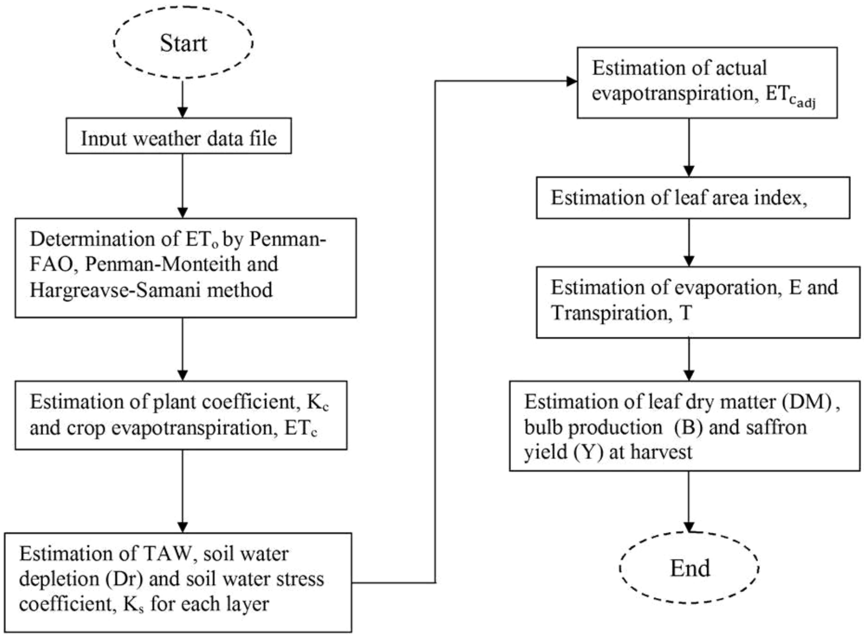

Figure 1. Schematic of saffron yield estimation model.

Model output file

This output file contained six Tables with Access format including:

- ET_o table contained calculated daily ET_o by Hargreaves-Samani, Penman-FAO and Penman-Monteith (mm d^{-1}).
- ET_c table contained daily root depth (cm), crop coefficient (K_c) and daily crop evapotranspirtion (mm d^{-1}).
- Water balance table contained deep percolation (mm), soil water stress coefficient (K_S), readily available water depletion fraction and actual ET, ET_a (mm d^{-1}), volumetric soil water content (%) in each quarter of root zone and mean volumetric soil water content (%) in the root zone at beginning of each day.
- LAI table contained leaf area index and daily soil surface evaporation (mm d^{-1}).
- Yield table contained seasonal transpiration (mm), seasonal top dry matter weight (kg ha^{-1}), seasonal corm weight (kg ha^{-1}) and saffron yield (kg ha^{-1}).

Main model and sub-models

Reference evapotranspiration

The reference evapotranspiration (ET_0, mm d^{-1}) was determined using FAO-Penman [Eq. (1)] (Doorenbos and Pruitt, 1977), Penman-Monteith [Eq. (2)] (Allen et al., 1998) and Hargreaves-Samani [Eq. (3)] (Hargreaves and Samani, 1985) equations.

$$ET_o = C\left[0.408 \times W \times R_n + 0.27(1-W)F_u(e_s - e_a)\right] \quad (1)$$

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

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

Where T is the average daily temperature at 2 m height (^oC); 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$^oC^{-1}$; γ is the psychrometric constant in kPa$^oC^{-1}$ and U_2 is the daily wind speed at 2 m height in m s^{-1}.

$$ET_o = 0.0023 \times R_n \times \left(T + 17.8\right)\left(T_{max} - T_{min}\right)^{0.5} \quad (3)$$

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

All equations for calculating ET_o were obtained from the study of Razzaghi and Sepaskhah (2012) which they calibrated and validated all the three ET_o equations [Eqs. (1), (2) and (3)] for the same study region. However, FAO-Penman [Eq. (1)] was used for ET_o determination in this study.

Crop evapotranspiration

Crop evapotranpiration (ET_c) was determined as fallows (Allen et al., 1998):

$$ET_c = K_c \times ET_o \quad (4)$$

$$K_c = a_o + a_1(DAFI)^2 + a_2(DAFI)^3 + a_3(DAFI)^4 \quad (5)$$

Where K_c is the crop coefficient, DAFI is the number of days after first irrigation and a_o, a_1, a_2 and a_3 are constants. The equation was derived from the data given in the study of Yarami et al. (2011) for the first and second and from Shirmohammadi-Aliakbarkhani (2002) for the third year (Table 1). In this model the Eq. (5) is not a calibration variable for validation of the model. The values of maximum K_c for the first, second and third year of plantation were 0.96 and 1.15 (Yarami, 2011) and 1.15 (Shirmohammadi-Aliakbarkhani, 2002), respectively.

Table 1. Coefficients of multiple regression equation [Eq. (5)] for determination of crop coefficient of saffron at different growing seasons.

Age of saffron field	a_0	a_1	a_2	a_3	R^2
First year	0.36761	0.00019	-1.70×10^{-6}	3.68×10^{-9}	0.95
Second year	0.40219	0.00023	-2.07×10^{-6}	4.46×10^{-9}	0.94
Third year and next	0.35085	0.00022	-1.95×10^{-6}	4.25×10^{-9}	0.96

Actual evapotranspiration

Under soil water stress condition, actual evapotranspiration (ET_a) is not further equal to ET_c and was calculated as follows (Allen et al., 1998):

$$ET_a = K_s \times ET_c \quad (6)$$

Where K_s is the soil water stress coefficient [Eq. (7)] which is dimensionless and varies between 0 and 1. In certain conditions of no stress, K_s is higher than 1.0, which physically means no water stress and it should be taken as 1.0. The K_s depends on soil total available water in the root zone (TAW in mm) and soil water deficit in the root zone (D_r in mm) and fraction of TAW that a crop can extract from root zone without suffering water stress (p) (Allen et al., 1998).

$$K_s = \frac{TAW - Dr}{(1-p)TAW} \quad (7)$$

$$p = p_t + 0.04(5 - ET_c) \quad (8)$$

In Eq. (8), p is the actual coefficient of readily available water and p_t is the coefficient of soil available water at ET_c of 5 mm d^{-1} considered as 0.29 for saffron (Sepaskhah and Yarami, 2009). Soil water depletion at the end of each day for each soil layer (a total of 4 layers) was also calculated using soil water balance [Eq. (9)].

$$D_{r,i} = D_{r,i-1} + P_i + R_{O,i} - I_i - C_{R,i} + ET_c + D_{P,i} \tag{9}$$

Where $D_{r,i}$ is the soil water deficit in the root zone of day i in mm; $D_{r,i-1}$ is the soil water deficit in the root zone at the end of day i-1 in mm; P_i is the daily precipitation in mm; $R_{O,i}$ is the soil surface runoff in mm; I_i is the applied irrigation water infiltrated in the soil in mm; $C_{R,i}$ is the daily capillary rise from groundwater in mm; and $D_{P,i}$ is the daily deep percolation to below the root zone in mm. To begin the soil water balance calculation, the initial soil water deficit ($D_{r,i-1}$) should be estimated by the following equation:

$$D_{r,i-1} = 1000 \times (\theta_{fc} - \theta_{i-1}) \times z_r \tag{10}$$

Where θ_{fc} is the volumetric soil water content at field capacity in $cm^3\ cm^{-3}$; θ_{i-1} is the mean volumetric soil water content in the root zone at day i-1 in $cm^3\ cm^{-3}$; and z_r is the root depth in m. In this model root depth was divided in-to four layers with same thickness but with different water absorption as 40%, 30%, 20% and 10% of actual evapotranspiration (from top to bottom layers). In rain-fed conditions, soil water content in the soil surface layer (i.e., soil layer above the corm) is almost air dry. Therefore, the first infiltrated precipitation should be used to raise the soil water content at surface layer to PWP and extra infiltrated precipitation is used as crop uptake. In this case, the value of $D_{r,\ i-1}$ is estimated as follows:

$$D_{r,\ i-1}=1000(\theta_{fc}-1/2\theta_{PWP})z_{ri} \tag{11}$$

Furthermore, in rain-fed conditions precipitation interception of 2.0 mm has been considered as precipitation loss and effective precipitation is used in the water balance equation as follows:

$$\text{If } P<2.0 \text{ mm}, P_e=0 \tag{12}$$

$$\text{If } P\geq 2.0 \text{ mm}, P_e=P-2.0 \tag{13}$$

Where P_e is the effective precipitation.

The value of $C_{R,i}$ is dependent of the groundwater depth. Since the groundwater depth in the study area was deeper than 30 m, therefore, the value for $C_{R,i}$ was considered as negligible (Sepaskhah et al., 2003). The value of $D_{P,i}$ after irrigation or a heavy rain was estimated by the following equation:

$$D_{P,i} = P_i - R_{O,i} + I_i - ET_c - D_{r,i-1} \tag{14}$$

In Eq. (14), it is assumed that the soil water content is at field capacity at the same day of wetting, so, the $D_{r,i}$ in Eq. (14) becomes zero. The value of $D_{P,i}$ was considered negligible when the soil water content was less than field capacity.

Root depth (z_r) in each day of growing season was determined according to Borg and Grimes (1986) as follows:

$$Z_r = DA + R_{DM} + [0.5 + 0.5\sin(3.03\frac{D_{AS}}{D_{TM}} - 1.47)] \tag{15}$$

Where DA is the planting depth of saffron which is usually 20 cm for saffron, however it may be different for various plantations, R_{DM} is the maximum root depth of saffron (0.45 m for saffron), D_{AS} is number of days after planting and D_{TM} is the days at maximum root depth (173 days). According to Shirmohammadi-Aliakbarkhani (2002) D_{TM} occurred at 85% of total growing season period. Therefore, when D_{TM} is not available model consider 85% of the total growing season as D_{TM}. Furthermore, root depth should not be deeper than wetting front after water infiltration and redistribution.

Yield estimation

In order to determine daily leaf area index (LAI), the following regression equation-which was derived from the data obtained from study of Yarami (2008) on saffron-considering soil available nitrogen (N, kg ha^{-1}) was used in this study as follows:

$$LAI = 0.862 \times (1 - EXP\{-[\frac{ETa}{139.74})^2]\} \tag{16}$$

Where ET_a in Eq. (16) is determined by Eq. (6). Equation (16) is valid until 150 days after first irrigation for saffron and after that LAI is reduced by a linear equation as follows:

$$LAI = -0.00961(DAFI-150) + LAI_{150} \quad \text{for} \quad DAFI>150 \tag{17}$$

Where DAFI is the number of days after first irrigation and LAI_{150} is the LAI at DAFI of 150.

To determine the soil evaporation [Eq. (18)], first the following exponential equation was derived from the data obtained from study of Yarami (2008) to determine the ratio of evaporation to actual evapotranspiration as follows:

$$\frac{E}{ETa} = EXP(-1.15 \times LAI) \quad (18)$$

$$E = (\frac{E}{ET_a}) \times ET_a \quad (19)$$

When irrigation or precipitation interval increased, surface evaporation is reduced and its value reached a negligible amount at interval of 20 days and later and ET_a is occurred as transpiration (T).

The crop transpiration (in mm) therefore calculated by subtracting determined evaporation from actual evapotranspiration ($T = ET_a - E$). Total dry matter production [Eq. (20)] was determined using transpiration and the difference of saturated vapour pressure and actual vapour pressure [Eqs. (21) and (22)].

$$Y_t = 2.944 \times [\frac{T}{(e_s - e_a)}] \quad (20)$$

$$e_s = 33.8639\left\{\left(0.00738T_a + 0.8072\right)^2 - 0.000019(1.8T_a) + 0.001316\right\} \quad (21)$$

$$e_a = e_s \times RH \quad (22)$$

Where T is the seasonal transpiration in mm, Y_t is the total dry matter production in kg ha^{-1}, e_s is the saturated vapor pressure in kPa, e_a is the actual vapor pressure in kPa, T_a is the average of temperature from the beginning of growing season to the day of calculation (^oC) and RH is the relative humidity.

Corm is the saffron organ that produces saffron flower. Corm production is a function of transpiration as follows:

$$B=57.18\times T, \qquad R^2=0.97 \tag{23}$$

Where B is the corm yield in kg ha^{-1} and T is the seasonal transpiration in mm. Eq. (23) was determined based on data obtained from stressed and non-stressed conditions. It should be noted that saffron propagation is based on corm plantation. Therefore, corm production should be estimated by saffron yield model that is possible by using Eq. (23).

The relationship between harvest index (HI) and transpiration was determined using Eq. (24) and the coefficient of this equation was fitted based on the data of HI and T from study of Azizi-Zohan et al. (2009) and Monfared (2005).

$$HI = 3.0\times 10^{-5}\times T \tag{24}$$

Finally the saffron yield (Y in kg ha^{-1}) was calculated as follows:

$$Y = Y_t \times HI \tag{25}$$

It is indicated that the Eq. (24) is not an appropriate function to estimate HI that can be used for saffron yield estimation in Eq. (25). Therefore, saffron yield (Y) was estimated from a relationship between Y and corm yield (B) as follows:

$$Y=4.31\times 10^{-2}\times B^2 \tag{26}$$

Where Y is the saffron yield in kg ha^{-1} and B is the corm yield in kg ha^{-1}. Eq. (26) was determined based on data obtained from stressed and non-stressed conditions. It should be noted that corm yield is estimated by Eq. (23) that is a function of transpiration. Therefore, by substitution of Eq. (23) in Eq. (26), saffron yield is obtained as a quadratic function of transpiration.

Model development data

Data for model development were obtained from Yarami et al. (2011), Azizi-Zohan et al. (2009) and Monfared (2005) as indicated in Table 2.

Table 2. Data source for different parameters used in model development and validation.

Purpose	Data	Source
Calibration	Crop coefficient (K_c)	Yarami et al. (2011)
	Evapotranspiration (ET_c)	Yarami et al. (2011)
	Soil water content	Yarami et al. (2011
	Leaf area index	Yarami et al. (2011
	Soil evaporation rate	Yarami et al. (2011)
	Leaf dry matter	Azizi-Zohan et al. (2009) Monfared (2005)
	Corm yield	Azizi-Zohan et al. (2009) Monfared (2005)
Validation	Soil water content	Shirmohammadi-Aliakbarkhani (2002)
	Leaf area index	Shirmohammadi-Aliakbarkhani (2002)
	Leaf dry matter	Shirmohammadi-Aliakbarkhani (2002)
	Corm yield	Shirmohammadi-Aliakbarkhani (2002)
	Saffron yield	Shirmohammadi-Aliakbarkhani (2002) Alavi-Shahri (1995)

Yarami et al. (2011)

The experiment was conducted in Badjgah Agricultural Experiment Station of Shiraz University located 16 km north of Shiraz, Islamic Republic of Iran (a semi-arid region with warm summer) with longitude and latitude of 52° 2′ E and 29° 56′ N, respectively and altitude of 1810 m above the mean sea level. The soil texture of the experimental site up to 50 cm depth is silty clay loam, with soil water content at field capacity and permanent wilting point equal to 0.29 cm^3 cm^{-3} and 0.109 cm^3 cm^{-3} for 0-15 cm depth and 0.38 and 0.114 cm^3 cm^{-3} for the 15-30 cm depth and 0.39 and 0.157 cm^3 cm^{-3} for the 30-120 cm depth, respectively. Soil bulk density is 1.35 g cm^{-3}at 0-20 cm depth. Mean annual precipitation is 399 mm, most of which occurs during autumn and winter. Mean monthly temperature ranges from 3.5 ˚C in January to 26 ˚C in July.

Three water balance lysimeters and their surroundings areas as buffer zone were used for this research. These lysimeters were installed in the middle of a field. The diameter and depth of the lysimeters were 1.5 and 1.7 m, respectively and they were equipped with a drainage system. The distance between two neighboring lysimeters was 1.5 m. Individual aluminum tubes were installed in all three lysimeters to a depth of 110 cm to measure soil water content by a neutron probe.

Saffron corms were planted on 12 September 2006 in three lysimeters and 150 m^2 of the surrounding area, in rows 40 cm apart (three rows in each lysimeter) and with a depth of 15-20 cm and a density of 6.0 Mg ha^{-1}. Fertilizers were applied as manure at the rate of 40 Mg ha^{-1} before planting and triple super phosphate at the rate of 100 kg ha^{-1} before the first irrigation. At the beginning of the second growing season, 22.5 Mg ha^{-1} manure was added to the lysimeters and surrounding field and the fields were then irrigated.

The first irrigation was applied on 27 and 28 October in the first and second year, respectively. Soil water content was measured approximately every two weeks to a depth of 105 cm in each lysimeters, using a neutron scattering method at 7-day intervals. The lysimeters and surrounding fields were watered by basin irrigation, using a pipe equipped with a flow meter to ensure the application of enough water to avoid water stress. When necessary (when there was no precipitation), soil water was raised to field capacity, after measuring soil water content considering a root depth of about 60 cm. The numbers of irrigation events during the first and second year were 5 and 12, respectively. It should be mentioned that the total amount of precipitation in the first and second year of experiment was 392 and 124 mm, respectively. The saffron potential evapotranspiration (ET_c) was measured using soil water balance during the growing season as described by Yarami et al. (2011).

In the study of Yarami et al. (2011), soil surface evaporation was measured by installing microlysimeter between two rows of plants, in the middle of each lysimeter for the two growing seasons. The micro-lysimeters were PVC pipes of 100 mm internal diameter and 300 mm height. A porous plate was installed in the bottom of each microlysimeter. All microlysimeters were filled with soil similar to the main lysimeters. Evaporation (E) in each lysimeter was determined by weighing the microlysimeters at three-or four-day intervals. These data were then used to determine soil evaporation rates at the measured intervals. The measured values are accounted for by including changes in plant cover during the growing season. Saffron transpiration (T) was estimated as the difference between ET_c and E.

Recent research by Sepaskhah and Fooladmand (2004) has shown that the best method for calculating reference evepotranspiration (ET_o) in Badjgah area is the Penman-FAO equation. Therefore, ET_o for each irrigation interval was calculated using this equation as described by Doorenbos and Pruitt (1977). Weather data were obtained from weather station near to the experimental site. Single crop coefficient (K_c) was determined as the ratio of ET_c to ET_o as described by Allen et al. (1998).

Leaf area index

Leaf area index (LAI) is the ratio of plant leaf area to the area of land that is devoted to the plant. Plant leaf area was determined in different growth stages by measuring the leaf length of several plants and converting them to the leaf area using the following equation (Yarami, 2008):

$$A=0.0072\times L^2+1.074 \quad (27)$$

Where A is the leaf area in cm^2 and L is the leaf length in cm.

Azizi-Zohan et al. (2009) and Monfared (2005)

A field study (Azizi-Zohan et al., 2009) was conducted for two years in the same area of Yarami et al. (2011). Field preparation and fertilizer application was also similar to those in Yarami et al. (2011). At the beginning of first growing season in September 1998, 4.8 Mg ha^{-1} of saffron corm with mean weight of 3.8 g each was planted at a depth of 15 cm with 2 cm distance on rows. The rows were 35 cm apart. The experiment consisted of basin irrigation and three irrigation intervals (12, 24 and 36 days) plus rain-fed treatments. For the rain-fed treatment and the first year, it was necessary to irrigate the plots at the start of the season to ensure plant establishment. The experimental design was complete randomized block with four replications. The area of each experimental plot was 24 m^2, with 12 rows of 6 m long. The plots were irrigated on 18 October 1998. The irrigation water was applied using a flexible hose. The amount of irrigation water was measured by a volumetric flow meter. The amount of irrigation water was determined by increasing the soil water content to the field capacity in the root zone. Access tubes were placed in the plots to a depth of 90 cm to monitor soil water content with scattering neutron probe. For the 0-15 cm layer, water content was measured by gravimetric method.

Saffron flowering started 7-10 days after breaking the surface crust. The flowering period lasted for 15-20 days. Saffron flowers were picked every morning from the entire plots (side rows not included), before the air warmed up. The flowers were inspected during the day and the style and stigmas were separated from the periath. After harvest, second irrigation was applied after which the different irrigation intervals were imposed.

At the beginning of second growing season, 22.5 Mg ha^{-1} of animal manure was added to the field and the plots were irrigated. When soil reached the friable stage, top soil was plowed manually. In the second year, the same treatments were applied and the first irrigation was applied on 19 October 1999. At the end of each growing season, leaves were harvested from the two entire rows in the middle of plots to determine the leaf dry matter yield. To evaluate the two-year cumulative effects of irrigation treatments on corm production, samples were collected from each experimental plot in August 2000. These data and the saffron yield harvested in October 1999 were used in calibration of the model.

The established saffron field in the experiment of Azizi-Zohan et al. (2009) was used for two different studies conducted to examine the effects of irrigation regimes on saffron yield (Shirmohammadi-Aliakbarkhani, 2002; Monfared, 2005). Monfared (2005) studied the effects of different irrigation regimes on saffron growth and yield for three growing seasons (2002-2005). This experiment initiated in September 2002 and terminated in May 2005. Irrigation treatments were $1.0ET_c$, $0.75ET_c$ and $0.5ET_c$ with irrigation interval of 24 days and rain-fed treatment. Other experimental procedure was similar to that conducted by Azizi-Zohan et al. (2009). Results of experiment for three growing seasons obtained from Monfared (2005) were used in the model calibration.

Model validation data

Data for model validation were obtained from Shirmahammadi-Aliakbarkhani (2002) and Alavi-Shahri (1995) as indicated in Table 2.

Shirmohammadi-Aliakbarkhani (2002)

Validation data were obtained from Shirmohammadi-Aliakbarkhani (2002). This experiment was conducted in the growing season of 2000-2001 and 2000-2001 in the same saffron field that established in the study of Azizi-Zohan et al. (2009) for calibration. The irrigation treatments were the same as those used by Monfared (2005) with similar experimental procedure used by Azizi-Zohan et al. (2009) and Monfared (2005).

Alavi-Shahri (1995)

Another set of data for validation was obtained from Alavi-Shahri (1995). This experiment was conducted in Zahak Agricultural Experiment Station located at east of Iran (arid climate) with latitude of 30° 54' N, longitude of 61° 34' E and elevation of 495 m above the mean sea level. Soil texture is sandy loam (10% clay, 18.6% silt and 71.5% sand) with pH of 7.7. Volumetric soil water content at field capacity and permanent wilting point are 21.0% and 9%, respectively. In this experiment the effects of three irrigation regimes as 45%, 65% and 85% of class A pan evaporation on the saffron growth and yield were studied. This experiment was conducted for several years. However the data of the third growing season was used in model validation.

Model performance criteria

The outputs of the model were compared by the measured values using following statistical parameters:

$$NRMSE=(1/n\Sigma^{n}_{i=1}(X_i-Y_i)^2)^{0.5}/O \quad (28)$$

Where NRMSE is the normalized root mean square error, n is the number of observations, X is the measured values, Y is the estimated values and O is the mean values of measured data.

$$d=1-\{[\Sigma^{n}_{i=1}(X_i-Y_i)^2]/[\Sigma^{n}_{i=1}(|X_i-O|+|Y_i-O_e|)^2]\} \quad (29)$$

Where d is the index of agreement and O_e is the mean value of estimated data. The value of NRMSE and d approaches 0.0 and 1.0, respectively, for the accurate estimation. 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 is more accurate.

Results and Discussion

Model development

Evapotranspiration

In this study, the reference evapotranspiration (ET_o) was determined using Penman-FAO equation in the model. Measured ET_c was compared with the predicted ET_c in second year due to the fact that saffron field was more established and its vegetation cover was higher in second growing season with higher water requirement (Sepaskhah and Kamgar-Haghighi, 2009). Maximum vegetation cover usually occurs in third growing season and the model is capable to predict ET_c in this growing season. However, their values were not compared due to unavailable measured ET_c in this growing season. Furthermore, it is indicated that the model is capable to estimate the ET_c at different growth stages accurately and show its variation during the growing season (Figure 2). Predicted crop evapotranspiration (ET_c) for second growing season was compared with the measured ET_c (Yarami et al., 2011) in Figure 3. Linear relationship between measured and predicted parameters used for model development were analyzed by regression and the coefficients of regression, i.e., slope and intercept were analyzed statistically. The intercepts were not significant by t-test (Table 3), therefore the regression equation was forced to pass the origin of coordinates as intercept is equal to zero and the regression equation was considered as Y=aX. The linear relationship between measured and predicted ET_c was compared with 1:1 line by F-test. The slope of linear regression was not significantly different from 1 ($P<0.05$).

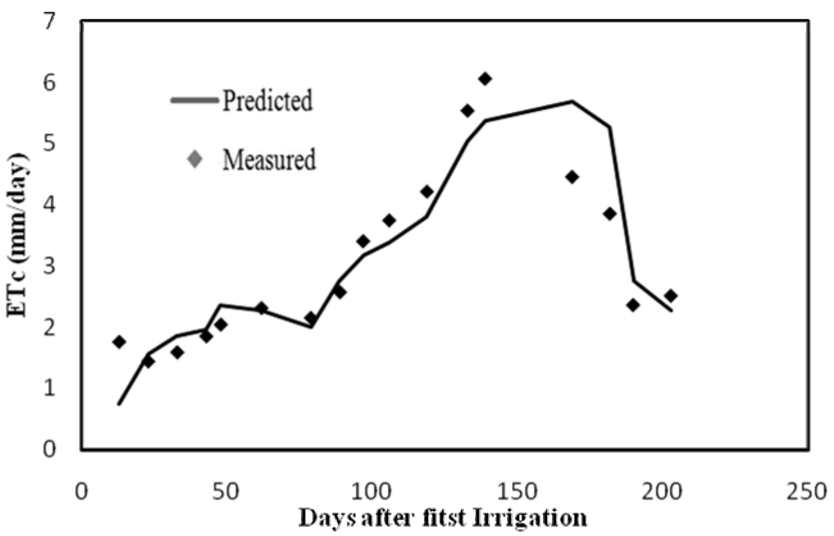

Figure 2. Measured (Yarami et al., 2011) and predicted crop evapotranspiration (ET_c) variation in second growing season.

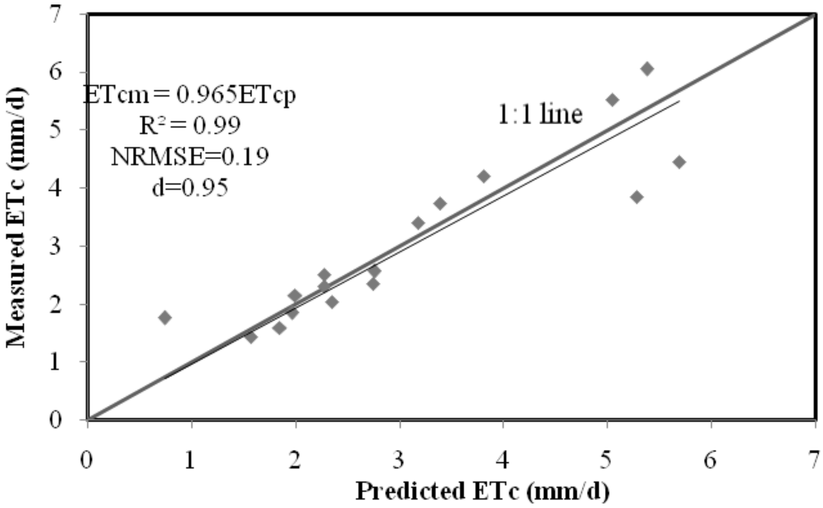

Figure 3. The relationship between measured (Yarami et al., 2011) and predicted crop evapotranspiration in second growing season.

Table 3. Results of statistical analyses for parameters used in model development and validation.

Pupose	Parameter	Equation	Probability level for intercept	NRMSE	Degree of accuracy*
Development	Evapotranspiration (ET_c)	Y=0.12+0.971X	0.76	0.190	Good
	Soil water content	Y=0.032+0.827X	0.28	0.126	Good
	Leaf area index	Y=0.13+0.788X	0.002	0.160	Good
	Soil evaporation rate	Y=0.16+0.985X	0.67	0.222	Fair
	Leaf dry matter	Y=140.2+0.878X	0.72	0.330	Poor
	Corm yield	Y=-3616+1.316X	0.14	0.190	Good
	Saffron yield	Y=-0.026+1.004X	0.97	0.156	Good
Validation	Soil water content	Y=0.014+0.950X	0.45	0.29	Fair
	Leaf area index	Y=0.090+0.859X	0.14	0.32	Poor
	Leaf dray matter	Y=-273.2+1.212X	0.57	0.724	Poor
	Corm yield	Y=-3214.8+1.312X	0.25	0.120	Good
	Saffron yield	Y=-0.524+1.179X	0.44	0.13	Good

● Based on ranking presented by Andarzian et al. (2011), NRMSE<10%=excellent; 10-20=good; 20-3-%=fair; >30%=poor.

This model was developed by different functions obtained for saffron in Bajgah area. Application of this model for different regions may require calibration of the used functional equations. One of these equations is the equation to determine the ET_o that may be different for various regions. Furthermore, the Eq. (3) may not be appropriate for different regions, therefore other equations, i.e., FAO Penman-Monteith, Hargreves-Samani equations may be suitable for other regions that may be used. These equations are inserted in the model and can be used accordingly. Another equation that may be calibrated for use in the model for other regions is Eq. (5). This equation can be obtained as a function of growing-degree-day.

Soil water content

To calculate soil water balance in the model, as mentioned above, soil depth was divided in to four layers and soil water content at each layer was determined at the end of the day. Then the soil water contents at different soil layers were averaged in the root zone. The relationship between the measured and predicted soil water content at root depth during second growing season of Yarami et al. (2011) was determined by linear regression analysis as follows (Figure 4):

$$\theta_m = 0.924 \times \theta_p \quad R^2=0.99, \quad NRMSE=0.126, d=0.93 \tag{30}$$

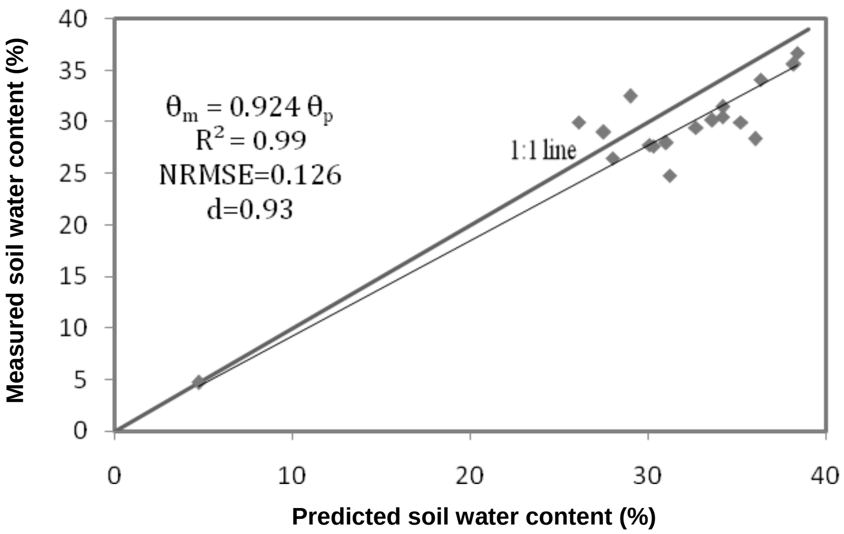

Figure 4. The relationship between measured (Yarami et al., 2011) and predicted volumetric soil water content in second growing season.

Where θ_m and θ_e are the measured and predicted soil water content (cm^3 cm^{-3}), respectively. The intercept was not statistically significant (Table 3), therefore the equation was forced to origin. Comparing Eq. (30) with 1:1 line, the slope of linear regression was not statistically different from 1 ($P<0.05$). The value of NRMSE for this prediction is 0.126 (Table 3), therefore the degree of accuracy is good.

Leaf area index

Measured and predicted LAI during the second growing season (Yarami et al., 2011) are shown in Figure 5. Leaf area index at early stage of growth was not predicted accurately. This may indicate that Eq. (16) is not accurate to estimate the LAI at the early growth stage of saffron. LAI increased during the vegetative growth period of saffron that is occurred during winter and it reached maximum value at the end of winter. LAI decreased during spring until leaf senescence at the end of growing season. Maximum LAI is about 0.9 that is much lower than that for field crops. The relationship between measured and predicted LAI is as follows:

$$LAI_m=0.10+0.858\ LAI_p \quad R^2=0.94 \qquad (31)$$

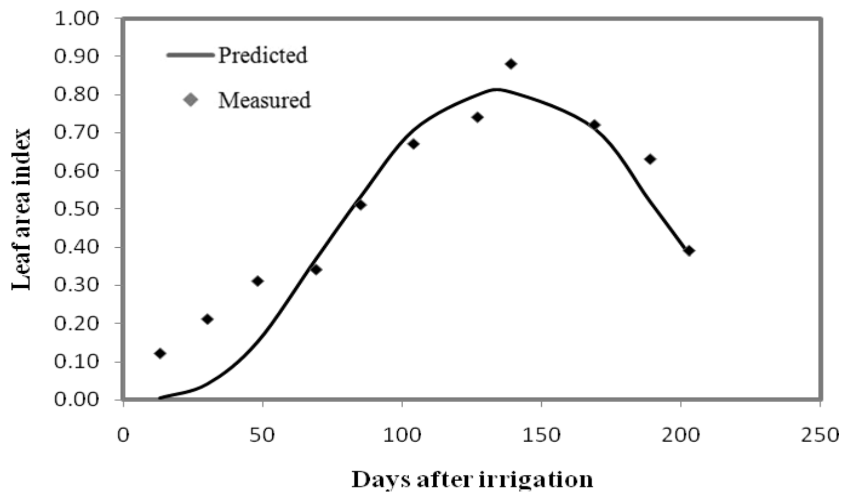

Figure 5. Measured (Yarami, 2008) and predicted LAI variation during the second growing season.

The linear relationship was compared statistically with 1:1 line and it showed that the slope of the linear regression equation was not different from 1.0, however the intercept is statistically different from zero (Figure 6). By considering the value of NRMSE of 0.160 (Table 3) it is indicated that the LAI prediction by the model is good.

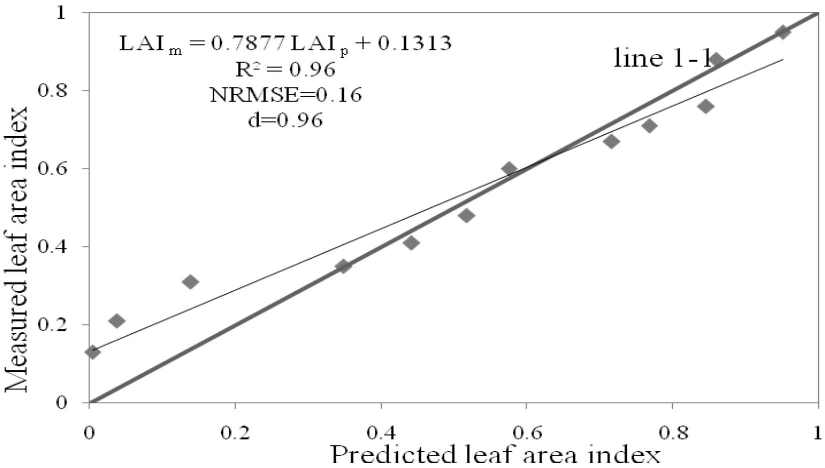

Figure 6. The relationship between measured (Yarami, 2008) and predicted LAI in the second growing season.

Soil surface evaporation

Measured and predicted soil surface evaporation rates (E) at different times during the growing season are compared in Figure 7. Measured E was obtained from microlysimeters. Relationship between measured and predicted E indicated that the intercept was not statistically significant (Table 3), therefore it was forced through origin. The line Y=aX was compared with 1:1 line statistically. The slope of linear regression equation was not statistically different from 1.0 ($P<0.05$). Therefore, it is indicated that the model is capable to predict the soil surface evaporation fairly accurate.

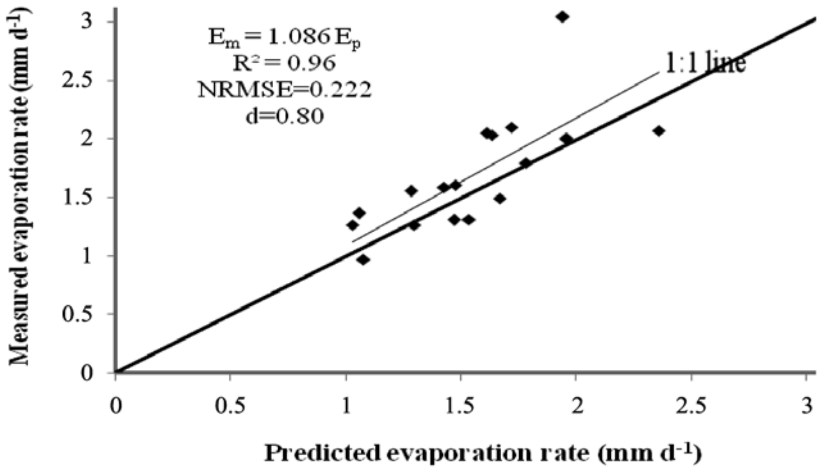

Figure 7. The relationship between measured (Yarami et al., 2011) and predicted soil surface evaporation rate in the second growing season.

Yield prediction

Measured and predicted yields were obtained from Azizi-Zohan et al. (2009) for second growing season and Monfared (2005) for fourth to sixth growing seasons. The measured data were obtained from basin irrigation with irrigation intervals of 12, 24 and 36 days and rain-fed treatment (Azizi-Zohanet el., 2009) and different irrigation regimes of $1.0ET_c$, $0.75ET_c$, $0.50ET_c$ and rain-fed (Monfared, 2005). The measured and predicted leaf dry matter, corm yield and saffron yield are compared in Figure 8. Linear relationships were obtained between the measured and predicted values, however the intercept was not statistically significant by t-test (Table 3). Therefore, the linear regression was passed the origin (intercept=0) as Y=aX. The slopes of linear regression fitting to the three variables were not statistically different from 1. However, the NRMSE and d values for leaf dry matter prediction (0.33 and 0.7, respectively) are high and low, respectively, indicating that the errors are relatively high. The values of NRMSE and d for corm and saffron yields (0.19 and 0.85 for corm; 0.156 and 0.96 for saffron yield, respectively) are lower and higher than those obtained for leaf dry matter, respectively indicating that the errors are relatively low for corm and saffron yields. Therefore, the model predicted the corm and saffron yields fairly well. It is clear that yield is lower in deficit irrigation and higher in full irrigation. Therefore, the model is developed well and it is efficient in saffron yield prediction.

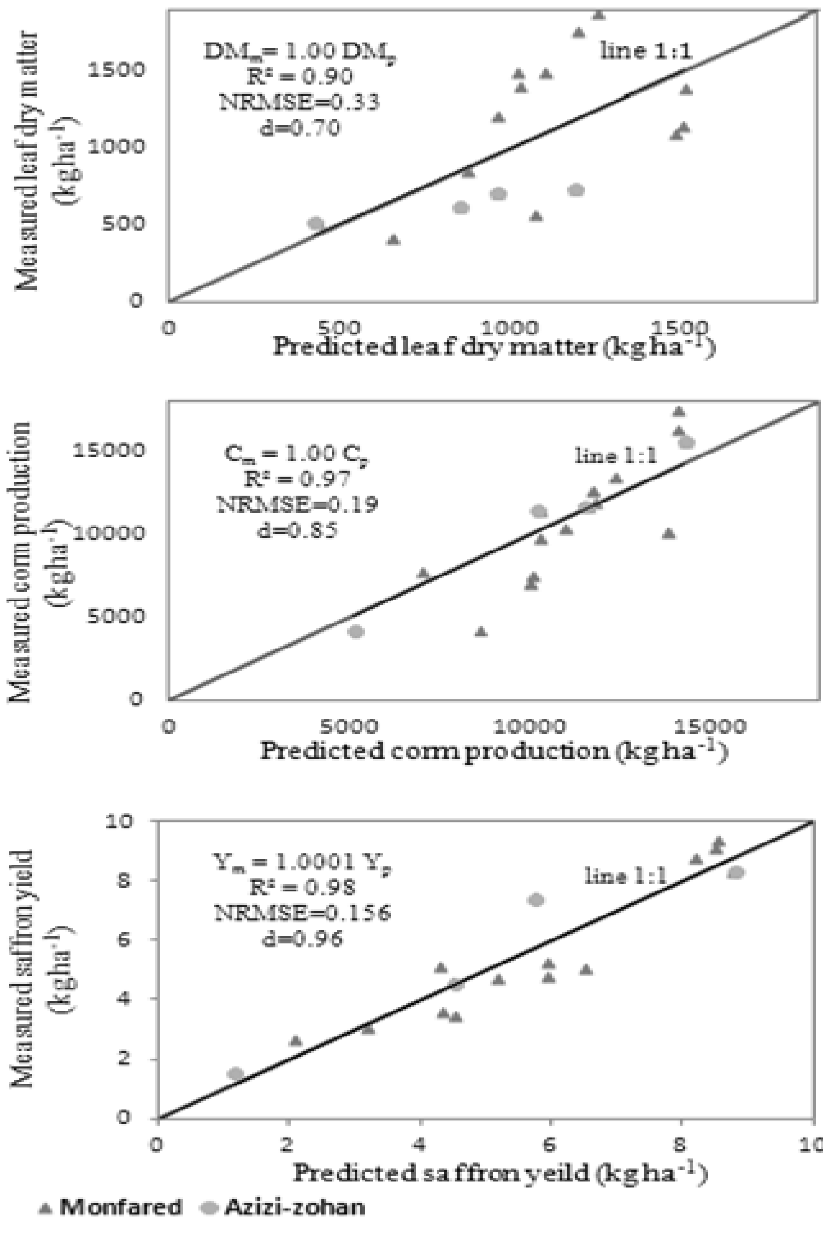

Figure 8. The relationship between measured (●: Azizi-Zohan et al., 2009; ▲: Monfared, 2005) and predicted leaf dry matter (top) corm (middle) and saffron yield (bottom) in the second and fourth to sixth growing seasons.

Validation

Shirmohammadi-Aliakbarkhani (2002) data

Soil water content

Seasonal ET_c was not measured by Shirmohammadi-Aliakbarkhani (2002). Therefore, the measured and predicted ET_c could not be compared. However, relationship between measured and predicted soil water content is shown in Figure 9. The linear regression showed that the intercept was not statistically significant (P<0.05, Table 3). Therefore, it is forced to pass the origin. Finally, the linear regression line (Y=aX) which was fitted to the data was compared with 1:1 line. The slope of the linear regression was not statistically different from 1 (P<0.05). This confirmed the ability of this simple model for fair estimation of soil water content (Table 3), however its error (NRMSE=0.29) is rather high due to a higher scattering of the data and low value of d, i.e., 0.73 in Figure 9.

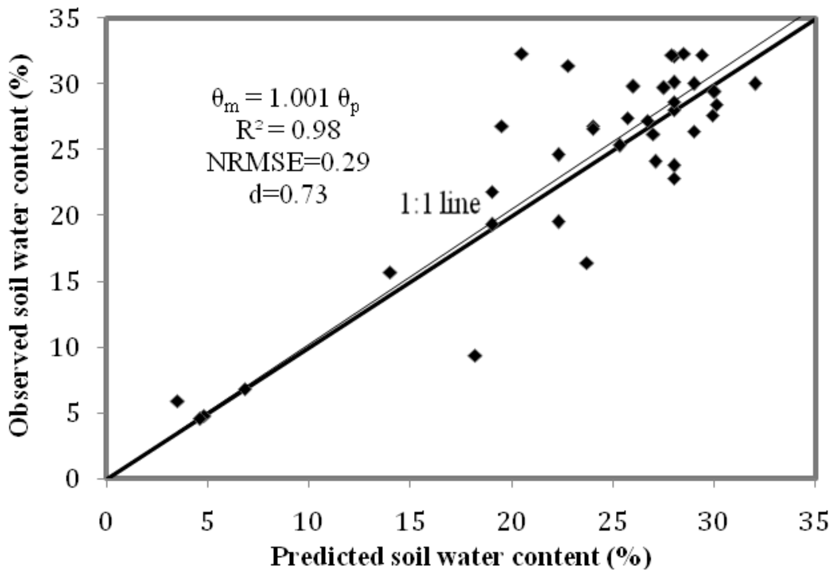

Figure 9. The relationship between measured (Shirmohammadi-Aliakbarkhani, 2002) and predicted volumetric soil water content in the third growing season.

Leaf area index

Relationship between the measured and predicted leaf area index (LAI_m and LAI_e, respectively) was obtained by linear regression as follows (Figure 10):

$$LAI_m = 1.003 \times LAI_p \quad R^2=0.94 \tag{32}$$

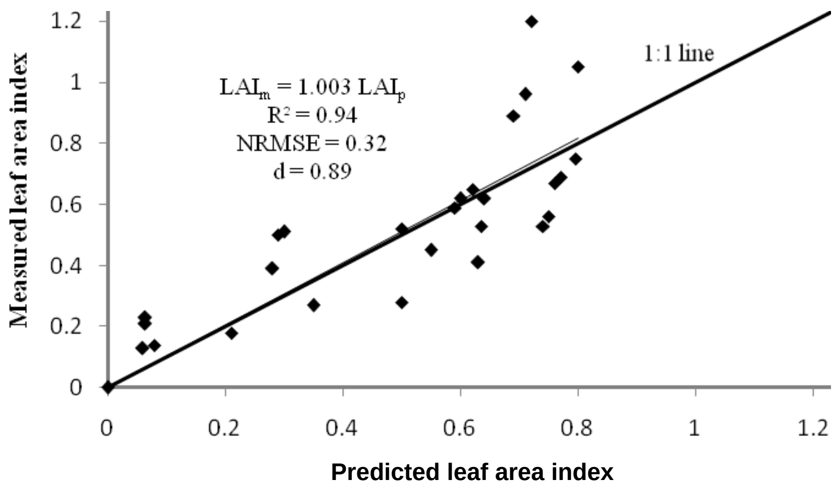

Figure 10. The relationship between measured (Shirmohammadi-Aliakbarkhani, 2002) and predicted LAI in the third growing season.

The relationship between measured and predicted leaf area index showed that the intercept is statistically non-significant. Therefore, it was passed to origin (Y=aX). Finally, Y=aX was compared with 1:1 line. The value of slope was not different from 1 (P<0.05). However, its error (NRMSE=0.32) is rather high due to a higher scattering of the data in Figure 10. Therefore, LAI prediction by model is rather poor (Table 3).

Variation of measured and predicted LAI during growing season were drawn for all treatments in third growing season (Shirmohammadi-Aliakbarkhani, 2002) and are shown in Figure 11. The model was able to estimate the LAI well as LAI was increased by increasing irrigation amounts. However, the model was not able to predict the maximum LAI very accurately especially under irrigated conditions. Due to this shortcoming, NRMSE was 0.32 that is relatively high. It is clear that the model overestimated the LAI in the middle of the growing season considerably while the underestimation early in the season and late in the season are not as large as the overestimation. This might be due to the occurrence of some uncertainty in Eqs. (16) and (17) that show the relationship between LAI and ET_a. By obtaining different relationships between LAI and ET_a under different environmental conditions the estimation of LAI should be improved.

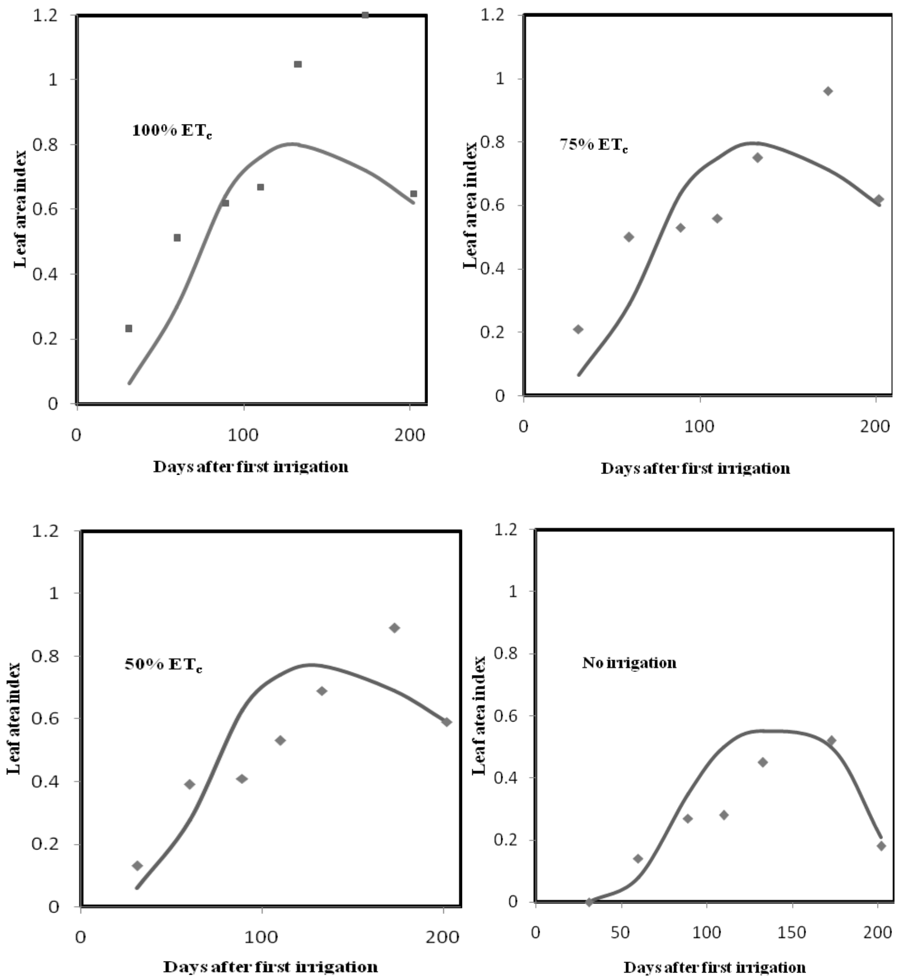

Figure 11. Measured (Shirmohammadi-Aliakbarkhani, 2002) and predicted LAI variation during the third growing season.

Yield prediction

Leaf dry matter, corm and saffron yields in the third growing season were reported by Shirmohammadi-Aliakbarkhani (2002) and were compared with those predicted by the model (Figures 12 and 13). Relationship between measured and predicted leaf drymatter (DM_m and DM_p, respectively) and corm yield (B_m, B_p, respectively) and saffron yield (Y_m and Y_p, respectively) were obtained by linear regression as follows:

$$DM_m = 0.877 \times DM_p \quad R^2=0.961 \tag{33}$$

$$B_m = 0.986 \times B_p \quad R^2=0.986 \tag{34}$$

$$Y_m = 1.135 \times Y_p \quad R^2=0.975 \tag{35}$$

Statistics of t-test for the intercept of these equations indicated that it is not significant and the regression line can be passed to origin. Comparing the linear regression (Y=aX) for different yields with line 1:1 showed that the slopes of all regressions were not statistically different from 1 ($P<0.05$), which indicated that the model was able to predict corm and saffron yields fairly well. It is clear that yields are lower in deficit irrigation and higher in full irrigation. Therefore, the model is efficient in saffron yield prediction. However, the values of NRMSE for leaf dry matter is very high (0.72, Table 3) that indicated the prediction for leaf dry matter is not precise. The values of NRMSE for corm and saffron yield are 0.12 and 0.15, respectively, that are rather low and indicating an appropriate prediction of model for these traits.

Alavi-Shahri (1995) data

Yield prediction

In study of Alavi-Shahri (1995), irrigation treatments conducted with intervals higher than 20 days. Therefore, soil surface evaporation at days 20 and later after irrigation or precipitation occurrence was considered negligible. Furthermore, Alavi-Shahri (1995) measured fresh flower weight in different irrigation treatments and did not report the saffron yield. Therefore, an empirical relationship between saffron fresh flower weight and saffron yield presented by Sepaskhah (unpublished data) as follows:

$$Y = 10.113 \times F \tag{36}$$

Where Y is the saffron yield in g and F is the fresh flower weight in kg. Eq. (36) was obtained based on data presented by Yarami (2008). Therfore, Eq. (36) was used to convert the fresh flower weight reported by Alavi-Shahri (1995) to the saffron yield.

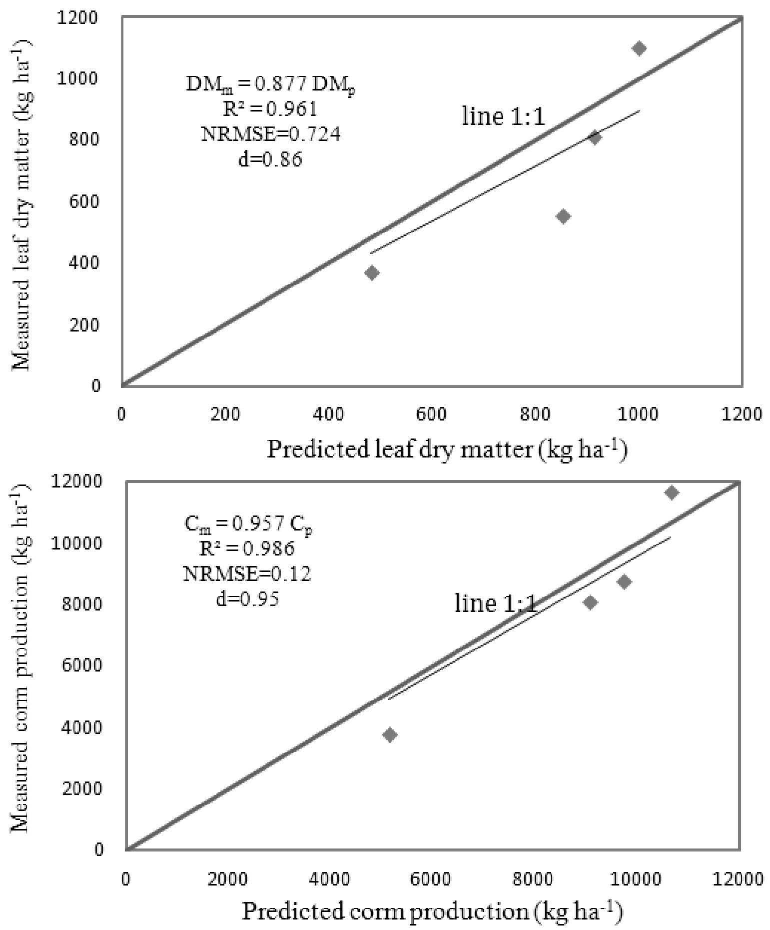

Figure 12. The relationship between measured (Shirmohammadi-Aliakbarkhani, 2002) and predicted leaf dry matter (top) and corm (bottom) in the third growing season.

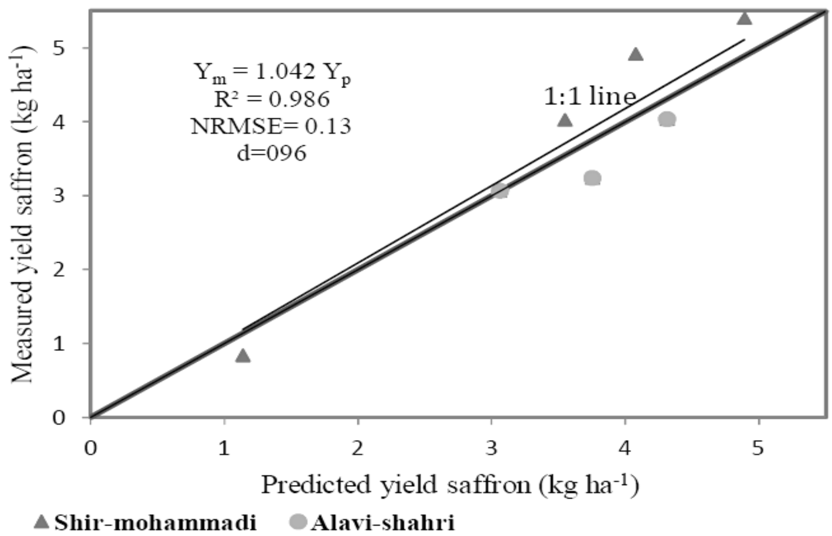

Figure 13. The relationship between measured (●: Alavi-Shahri, 1995; ▲: Shirmohammadi-Aliakbarkhani, 2002) in arid and semi-arid areas, respectively and predicted saffron yield in the third growing season.

Leaf dry matter, corm and saffron yields at the third growing season are predicted by the model. However, Alavi-Shahri (1995) only reported the fresh flower yield. The fresh flower yield was converted to the saffron yield by using Eq. (36). Then the measured and predicted saffron yield was compared in Figure 13. Relationship between measured and predicted saffron yield was obtained by regression analysis as follows:

$$Y_m = 0.923 \times Y_p \quad R^2=0.997, \quad NRMSE=0.09, \quad d=0.97 \tag{37}$$

Comparing the linear regression for saffron yield (Y=aX) with line 1:1 showed that the slope of regressions were not statistically different from 1 ($P<0.05$), which indicated that the model was able to predict saffron yield fairly well. It is clear that yield is lower in deficit irrigation and higher in full irrigation. Therefore, the model is efficient in saffron yield prediction. Overall, the measured and predicted saffron yield from different areas (Bajgah and Zahak) with various climatic conditions and irrigation regimes (Shirmohammadi-Aliakbarkhani, 2002; Alavi-Shahri, 1995) are compared in Figure 13. Furthermore, it is indicated that the data of Bajgah is consistent with those of Zahak.

Conclusions

In this study, saffron yield was modeled using simple equations in order to make it more applicable for farmers. The model was developed based on data from given study under basin irrigation with different regimes and validated based on independent data under basin irrigation systems. The root depth of saffron divided into four layers with similar thickness and simple volumetric water balance equation in various layers was used to simulate the soil water budget in which difference between field capacity and wilting point was taken as soil water capacity and excess water was considered as deep percolation. Root growth was simulated based on presented model by other researcher. Soil water content at any layer was calculated by water budget equation. The FAO-Penman, method was used to estimate the reference evapotranspiration (ET_o) and actual ET was calculated by soil water stress and crop coefficient that is related to the days after first irrigation. Leaf area index (LAI) was dependent to the actual ET. Evaporation from soil surface and transpiration from crop was predicted by the ratio of evaporation to actual ET that is related to LAI. Leaf dry matter and corm yield was determined as a function of crop transpiration and saffron yield was determined as quadratic function of corm yield. Therefore, saffron yield was a quadratic function of transpiration. In model development process the leaf dry matter was not predicted with acceptable accuracy. Therefore, the relationship between total dry matter and HI was not appropriate for yield prediction. In this case, the relationship between corm prediction and saffron yield was used for yield prediction. Furthermore, the relationship between LAI and ET_a may be different in different environmental conditions that should be considered in model use in various environmental conditions. In model validation prediction of leaf dry matter, leaf area index and soil water content was not very accurate. These might have been due to the use of less accurate relationship between LAI and ET_a for the validation conditions. Furthermore, it is indicated that corm yield determines the saffron yield that was the main parameter for saffron yield prediction. The results of comparison between predicted and measured values of different crop parameters were different however model was able to estimate corm yield and saffron yield properly.

Acknowledgement

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