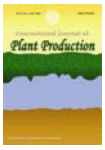

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Evaluation of macroscopic water extraction model for salinity and water stress in saffron yield production

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Abstract

Water scarcity and salinity are important limitations for saffron (*Crocus sativus* L.) production in arid and semi-arid regions. The purpose of this research was to study the interaction effects of water salinity and deficit irrigation on the macroscopic water extraction model for saffron. The effect of salinity and water stress on root-water uptake coefficient was determined by additive and multiplicative functions, and was compared with a recently purposed method. At every irrigation intervals, the root-water uptake coefficient α (h, h_o) was reduced as the soil osmotic head (h_o) decreased at higher salinity levels. Furthermore, the values of α (h, h_o) were reduced at higher irrigation intervals. Root-water uptake coefficient was reduced by decreasing in soil matric head (h) and soil osmotic head at salinity levels greater than control. The results indicated that the additive and multiplicative functions for root-water uptake were not suitable for prediction of root-water uptake coefficient of saffron to show the interaction effect of salinity and deficit irrigation on flower yield prediction. The Mass and Hoffman, and Homaee and Feddes multiplicative equations resulted acceptable estimation of α (h, h_o). Furthermore, saffron flower yield was predicted by using Homaee and Feddes α (h, h_o) and FAO transpiration reduction coefficient in production function presented by Stewart and his colleagues. Results indicated that the FAO method did not predict the flower yield properly, specially in high irrigation intervals and high salinity levels, but the Homaee and Feddes α (h, h_o) resulted in acceptable prediction of the saffron flower yield with a minimum error at salinity and water stress treatments with relative yield of greater than about 40%. Therefore, Homaee and Feddes equation is recommended for estimation of α (h, h_o) and flower yield of saffron.

Keywords: Sffron deficit irrigation; Saffron yield modeling; Root-water uptake coefficient.

Inroduction

Water scarcity and soil salinity are two important limitations for agricultural production in arid and semi-arid regions. Both salinity and water stress reduce root water uptake. In irrigated soils particularly in arid and semi-arid regions, plants are subjected to both salinity and water stress in different intensities. The effects of salinity and water stress on saffron yield (Sepaskhah and Yarami, 2009; Sepaskhah and Kamgar-Haghighi, 2009), and madder

(*Rubina tinctorum* L.) growth (Sepaskhah and Beirouti, 2009) have been reported. In these conditions, during an irrigation interval, evapotranspiration depletes the soil water content and consequently the matric, and osmotic head of the soil solution are reduced and these factors reduce root water uptake.

To quantify the root water uptake, the microscopic and macroscopic extraction approaches are used. The macroscopic approach readily used by many investigators (Feddes et al., 1978) that assumes the extraction term under non-stress conditions is simply equal to potential transpiration over root zone. As soon as the soil water pressure head reaches a critical value, the actual transpiration reduces linearly until the root-water uptake ceases completely (wilting point). This reduction quantified by the so-called reduction function. The macroscopic models basically do not account for saline conditions. Van Genuchten (1987), and Dirksen et al. (1993) incorporated different nonlinear osmotic head-dependent reduction functions in Feddes et al. (1978) model. Most of these are based upon the so-called multiplicativity concept that uses the product of the separate reduction terms for soil water osmotic and pressure heads. Recently proposed linear reduction function is neither additive nor multiplicative (Homaee and Feddes, 1999; Homaee et al., 2002), but was assumed both the intercept and slope of the reduction function increased with salinity. Homaee et al. (2002) verified their model by predicting the vegetative growth of alfalfa.

The purposes of this research were to evaluate the interaction effects of soil osmotic and pressure heads on root-water uptake coefficients of saffron by different theoretical concepts and measured values. Further, the application of these coefficients in prediction of saffron flower yield (reproductive growth) was evaluated.

Theory

Water uptake coefficient

Water flow in unsaturated soils described with Richards' equation (Richards, 1931). Including the root extraction term *S*, it is as follows:

$$\frac{\partial \theta}{\partial t} = C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial Z}(K(h)\frac{\partial h}{\partial Z} + K(h)) - S \tag{1}$$

where θ is the volumetric water content ($L^3\ L^{-3}$), t is the time (T), C is the differential soil water capacity (L^{-1}) that is equal to the slope $d\theta/dh$ of the soil water retention curve, h is the soil water pressure head (L), Z is the gravitational head, as well as the vertical coordinate (L) taken positive upward, K is the soil hydraulic conductivity ($L\ T^{-1}$), and S is the soil water extraction rate by plant roots ($L^3\ L^{-3}\ T^{-1}$). This is determined as follows:

$$S = \alpha(h.h_0)S_{\max} \tag{2}$$

where $S_{\max}$ is the maximum water uptake rate and $\alpha(h,h_0)$ is a dimensionless function of pressure and osmotic head. The available macroscopic reduction functions for the combined stresses are divided into two categories: additive, and multiplicative. The additive reduction function (Van Genuchten, 1987) is as follows:

(3) $$\alpha(h,h_0)=\frac{1}{1+(\frac{a_1 h+a_2 h_o}{h_{50}})^p}$$

where h_{50} is the soil water pressure head at which $\alpha(h)$ is reduced by 0.50, a_1 and a_2 are weighting factors and just for simplicity they are generally assumed being 1.0 thus giving linear additivity, and p is an empirical parameter, the value of p was found to be about 3.0 when the S-shaped function was applied to salinity stress data. The multiplicative reduction function proposed by Van Genuchten, (1987); Dirksen et al. (1993); Homaee et al. (2002); Mass and Hoffman (1977) and Homaee and Fedddes (1999). The multiplicative reduction function (Van Genuchten, 1987) is as follows:

(4) $$\alpha(h,h_0)=\frac{1}{1+[\frac{h}{h_{50}}]^{p_1}}\times\frac{1}{1+[\frac{h_0}{h_{050}}]^{p_2}}$$

where h_{o50} is the soil salinity at which water uptake is reduced by 0.50. Homaee et al. (2002) proposed the following equation for the combined stresses:

(5) $$\alpha(h,h_0)=\frac{1}{1+(\frac{1-\alpha_{01}}{\alpha_{01}})[\frac{h^*-h}{h^*-h_{\max}}]^{p_1}}\times\frac{1}{1+(\frac{1-\alpha_{02}}{\alpha_{02}})[\frac{h_0^*-h_0}{h_0^*-h_{0\max}}]^{p_2}}$$

where $h_{\max}$ and $h_{0\max}$ (the second threshold value) is the soil water pressure head and soil osmotic head beyond which the changes of h or h_0 no longer influence the relative transpiration significantly, h^*_o is the threshold soil water osmotic head corresponding to the threshold soil water salinity, h_o is the soil osmotic head corresponding to the soil water salinity, α_{01} and α_{02} is the relative transpiration at $h_{\max}$ and $h_{0\max}$ and p_1 and p_2 is given as follows:

(6) $$p_1=\frac{h_{\max}}{h_{\max}-h^*}$$

(7) $$p_2=\frac{h_{o\max}}{h_{o\max}-h_o^*}$$

The multiplicative reduction function proposed by Dirksen et al. (1993) is as follows:

(8) $$\alpha(h,h_o)=\frac{1}{1+(\frac{h_3-h}{h_3-h_{50}})^{p_1}}\times\frac{1}{1+(\frac{h_0^*-h_0}{h_0^*-h_{050}})^{p_2}}$$

where h_3 is the soil water pressure head threshold value, and h_4 is the soil water pressure head at wilting.

Maas and Hoffman (1977) proposed the following equation:

(9) $$\alpha(h,h_0)=\frac{h-h_4}{h_3-h_4}\times[1-\frac{a}{360}(h_0^*-h_0)]$$

where a is the yield reduction as percent per unit increase salinity of soil water as dS m^{-1}. Homaee and Feddes (1999) proposed the other equations that is basically a combination of linear and non-linear and differs conceptually from additive and multiplicative theories. In their equation it is assumed that each dS m^{-1} salinity beyond the threshold value (EC*) shifts the wilting point 360 cm to the left, and the equation is as follows:

$$\alpha(h,h_0)=\frac{h-(h_4-h_0)}{h_3-(h_4-h_0)}[1-\frac{a}{360}(h_0^*-h_0)] \tag{10}$$

This equation is valid for $h_o \leq h_o^*$ and $(h_4-h_o) \leq h \leq h_3$, respectively. The value of 360 cm is the conversion factor of soil water salinity to osmotic pressure head as suggested by Richards (1954).

Yield estimation approaches

Stewart et al. (1977) proposed the equation to obtain yield in water stress as follows:

$$1-\frac{Y_a}{Y_m}=\prod_{i=1}^{n}\left\{K_{y_i}\left[1-\frac{ET_{c-adj}}{ET_p}\right]_i\right\} \tag{11}$$

where Y_a is the actual crop yield (t ha^{-1}), Y_m is the maximum expected crop yield (t ha^{-1}), K_y is the relative yield response factor to water stress and vary over the growing season, i is the consecutive growing stages, n is the number of growing stages, ET_p is the potential crop evapotranspiration (no water stress) (mm d^{-1}), and $ET_{c\text{-}adj}$ is the adjusted crop evapotranspiration (mm d^{-1}) that is shown as:

$$ET_{c-adj}=K_s\times ET_p \tag{12}$$

where K_s is the transpiration reduction coefficient and dependent on available soil water that is vary between 0-1 and under salinity and water stress condition is given as follows (Allen et al., 1998):

$$K_s=\left[1-\frac{a}{K_y100}\left(EC_e-EC_{e-threshold}\right)\right]\times\left[\frac{TAW-Dr}{TAW-RAW}\right] \tag{13}$$

where D_r is the root zone depletion (mm), TAW is the total available soil water in the root zone (mm), RAW is the readily available water (mm), EC_e is the soil water electrical conductivity (dS m^{-1}) and $EC_{e\text{-}threshold}$ is the threshold soil water electrical conductivity (dS m^{-1}). After rearranging Eq (11) and combining Eq (12) and Eq (2), respectively, we obtain the following equations for relative yield under water and salinity stress:

$$\frac{Y_a}{Y_m}=1-K_y\left[1-\frac{\alpha(h,h_0)ET_p}{ET_p}\right] \tag{14a}$$

$$\frac{Y_a}{Y_m}=1-K_y\left[1-\frac{K_sET_p}{ET_p}\right] \tag{14b}$$

Application of Eq (14b) should usually be restricted to $EC_e < EC_{e\text{-}threshold} + 50/a$ and $K_y \leq 1.0$. For $K_y > 1.0$ it should predict $Y_a = 0$ at $K_s = 0$. In addition, the K_y values are given for only 23 crops by Doorenbos and Kassam (1979) and where K_y is unknown it is suggested to use $K_y = 1$ or may select the K_y for a crop that has similar behavior.

If K_s in Eq (12) is replaced by α (h, h_0) Eq (14a) is obtained which is a different method for calculation of $ET_{c\text{-}adj}$. Then, Eq (14a) is used to estimate relative yield and with knowing the maximum yield, Y_m, the value of actual yield, Y_a is estimated.

Materials and Methods

This research was conducted over two seasons in pots under a transparent shelter at the college of Agriculture, Shiraz University in 2006 and 2007. The soil was a loam taken from the top 20 cm layer. Some of the physico-chemical properties of this soil are shown in Table 1. The soil was air-dried, crushed to pass through a 2-mm sieve to save the large soil aggregates. Plastic pots with 23.5 cm high and 23 cm of diameter on the top and 19.0 cm in diameter at the bottom were filled with 7.3 kg of this air-dried soil with a gravel filter (2-4 mm gravel, 2 cm thick) at the bottom. Holes were drilled in the bottom of the pots for drainage. Manure (150 g) was mixed with the soil at a rate equivalent to 40 t ha^{-1}. The side walls of the pots were covered with glass wool for heat isolation. Twelve saffron corms with mean dry weight of 6.41 g (mean fresh weight of about 12.6 g), were planted in each pot at a depth of 10 cm on 10 September in 2006. This is equivalent to the corm intensity of a 3 to 4-year old field with economical yield. Each pot irrigated with tap water (EC = 0.5 dS m^{-1}) to field capacity on 27 October. At the time of first irrigation, triple super phosphate fertilizer was applied as a solution at a rate of 100 kg ha^{-1} (0.32 g pot^{-1}). After irrigation, flowering commenced and soil surface was tilled to facilitate flowering. During 3 weeks after the first irrigation, water was applied at 5-d intervals, then, irrigation and salinity treatments started.

Table 1. Physico-chemical properties of the disturbed soil and irrigation water analysis used in the pot experiment.

Physical property of soil		Chemical property of soil	
Sand (%)	40.0	Ca (meq l^{-1})	13.80
Silt (%)	47.0	Cl (meq l^{-1})	5.25
Clay (%)	13.0	Na (meql^{-1})	3.68
Field capacity (cm^3 cm^{-3})	0.36	EC_e (dS m^{-1})	0.89
Permanent wilting point (cm^3 cm^{-3})	0.19		
Bulk density (g cm^{-3})	1.24		

Irrigation water analysis

EC (dS m^{-1})	pH	Cl (meq l^{-1})	Na (meq l^{-1})	Ca (meq l^{-1})	HCO_3 (meq l^{-1})
0.5	7.95	2.00	0.89	3.80	6.16
1.7	8.01	17.50	3.47	13.00	4.86
2.9	7.70	27.00	5.45	18.00	4.86
4.0	7.91	41.00	6.93	29.00	4.86

Irrigation treatments consisted of four irrigation intervals (2, 4, 6, and 8-d coded W_0, W_1, W_2, and W_3, respectively). Salinity treatments of the irrigation water were at 0.5 (tap water), 1.7, 2.9, and 4.0 dS m^{-1} (S_0, S_1, S_2, and S_3) and were obtained by adding NaCl

and $CaCl_2$ to the tap water in equal equivalent proportion. Chemical analysis of the saline irrigation water is shown in Table 1. The experimental layout was a four × four way factorial arrangement with three replications. The amount of irrigation water used was determined by weighting the pots before each irrigation and raising the soil water content to field capacity. T achieve leaching, 30% more water was applied. Therefore, the mean amounts of irrigation water over different salinity levels were 712, 633, 546, and 451 mm. The maximum and minimum air temperatures were 37 ± 7 ˚C and 15 ± 5 ˚C, respectively. The maximum and minimum soil temperatures at depth of 10 cm were 22.0 and 1.0 ˚C, respectively.
Crop evapotranspiration determined by water balance as follows:

(15) $$ET = I - D_P$$

where ET is the crop evapotranspiration, in mm; I is the applied irrigation water, in mm; and D_p is the deep percolation, in mm. the value of D_p is the amount of drainage water measured between successive irrigations. The value of ET in W_0 treatment considered as crop potential evapotranspiration (ET_p).

Samples of soils from the pots were used to determine the soil water retention curve by a hanging water column and pressure plate apparatus (Soil Moisture Equipment Co., Santa Barbara, California, USA). The soil water retention equation was as follows:

(16) $$\theta = 0.1 + 0.33\left[1 + (|0.006 \times h|)^{1.29}\right]^{-0.225}$$

where θ is the soil volumetric water content in, $cm^3\ cm^{-3}$; and h is the soil water matric head, in cm.

The soil water content of pots before each irrigation was measured by weighing the pots. Drainage water was collected 13-times during the growing season. Electrical conductivities of the drainage water were determined during the growing season. Soil water content before each irrigation was converted to soil water matric head by using Eq (16).

After leaves senescenced from 27 April to 15 May 2007, they were harvested, they were harvested, dried in an oven under 65 ˚C for 48 h, and weighed.

The second growing season started on 27 October 2007 by irrigating the pots with water of different salinity levels and raising their water content to field capacity. Before irrigation, 90 g of manure applied to every pot at a rate of 22.5 kg ha^{-1}. After irrigation, second season flowering initiated and the irrigation treatments were imposed. Saffron flowers were picked each day and their fresh weights were determined. Flowering ended on 16 November 2007 and the total fresh flower weights were determined. At the end of flowering, the corms were separated from soil and the soil in the pots was sampled for chemical analysis. The rest of the soil was washed and the separated corms and roots were dried in an oven at 65 ˚C for 48 h. The oven dried corm and roots weighed separately.

Electrical conductivity of the drainage water was determined. Osmotic head of the drainage water as soil solution was estimated by the following equation (Richards, 1954):

(17) $$h_0 = -360 \times EC_{SS}$$

where h_o is the osmotic head in, cm; and EC_{ss} is the soil solution salinity in, dS m^{-1}. Soil water content before each irrigation was converted to soil water matric head by using the soil water retention equation [Eq (16)]. Similar pots filled with water to a height equal to the planted pots and placed between them to measure the daily free water surface evaporation by adding the evaporated water to the pots. The free surface water evaporation during the growing season was about 700 mm in the experimental conditions.

Results and Discussion

Root-water uptake coefficient

Root-water uptake coefficient [α (h, h_o)] is relative transpiration that obtained from ratio of the actual transpiration to the potential transpiration. In this study it was assumed that the relative transpiration is equal the relative evapotranspiration. Therefore, the adjusted evapotranspiration divided by the potential evapotranspiration for different treatments and the results were taken equivalent to the root-water uptake coefficient. Furthermore, the root-water uptake coefficients were estimated by Eqs (3), (4), (8), (9) and (10) proposed by different investigators. In these estimations, the corresponding values of soil matric and osmotic heads were determined by Sepaskhah and Yarami (2009) and are presented in Table 2. The value of a in Eqs (9) and (10) is 17.3% per dS m^{-1}(Spaskhah and Yarami, 2009). Relationships between the predicted values of α (h, h_o) by different equations and the measured values determined by linear regression analysis and the results are shown in Table 3.

Table 2. Input parameters for estimation of water reduction coefficient and yield of saffron.

Input parameter	Unit	Parameter value
h_3	cm	-709
h_{50}	cm	-2468
h_{max}	cm	-14675
h_o^*	cm	-522
h_{o50}	cm	-1562
h_{omax}	Cm	-2603
a	%/dS m^{-1}	17.3
K_y	-	1.79

Table 3. The results of F-test analysis for comparison of predicted water uptake function with measured values.

Equation number	Linear equation	R^2	n	SE	P	Slope	Intercept
						Probability level 5%	
Eqn (3)	α_p=1.47 α_m-0.64	0.75	48	0.129	2.41E-15	S	S
Eqn (4)	α_p =0.72 α_m -0.18	0.76	48	0.060	4.93E-16	S	S
Eqn (8)	α_p =0.96 α_m -0.29	0.79	48	0.075	4.33E-17	NS	S
Eqn (9)	α_p =0.92 α_m	0.52	48	0.099	8.32E-41	NS	-
Eqn (10)	α_p =0.91 α_m	0.56	48	0.096	2.68E-41	NS	-

The additive equation for root-water uptake coefficient proposed by van Genuchten (1987) [Eq (3)] predicted the values of α (h, h_o) very lower than the measured values. The slope and intercept of linear relationship between the estimated α (h,h_o) by additive function (van Genuchten, 1987) and the measured values was statistically higher than 1.0 and lower than 0.0, respectively. Furthermore, the multiplicative equation for root-water uptake coefficient proposed by van Genuchten (1987) [Eq (4)] predicted the values of α very lower than the measured values. The slopes and intercept of linear relationships between the estimated α (h, h_o) by multiplicative functions (van Genuchten, 1987) and the measured values were statistically lower than 1.0 and 0.0, respectively. The relationship between the estimated values of α (h, h_o) by Dirksen et al. (1993) equation [Eq (8)] and measured values is shown in Table 3. The linear equation for this relationship indicated that although the slope is close to 1.0, but its intercept is significantly different from zero. As a result, the Eq (8) predicted the values of α (h, h_o) very lower than the measured values. Therefore, it indicated that the additive and multiplicative equations by van Genuchten (1987) and Dirksen et al. (1993) are not appropriate for estimation of α (h, h_o) for saffron.

The estimated values of α (h, h_o) by Homaee and Feddes (1999) [Eq (10)] were close to those of measured values. The relationship between these values is shown in Figure 1. The estimated values of α (h, h_o) by Mass and Hoffman (1977) equation [Eq (9)] were the closest to those predicted by Homaee and Feddes (1999) equation [Eq (10)]. The relationship between the predicted [Eq (9)] and measured values of α (h, h_o) is shown in Figure 2 and it is determined by linear regression (Table 3). Finally, the slope and intercept of the linear relationship between estimated α (h, h_o) by the combination function (Mass and Hoffman, 1977; Homaee and Feddes, 1999) and the measured values were statistically close to 1.0 and 0.0, respectively. Therefore, the combination function of Mass and Hoffman (1977) and Homaee and Feddes (1999) are appropriate for estimation of α (h, h_o) for saffron.

Variation of root-water uptake coefficient with osmotic head

By decrease in soil osmotic head (-h_o), total soil water head is reduced and plant should spend more energy to uptake water. Figure 3 illustrates variation of root- water uptake coefficient with osmotic head for different irrigation intervals. At every irrigation interval, the root-water uptake coefficient was reduced as the soil osmotic head decreased at higher salinity levels. The slopes of these relationships at different irrigation intervals were not statistically different. However, the values of α (h, h_o) were reduced at higher irrigation intervals.

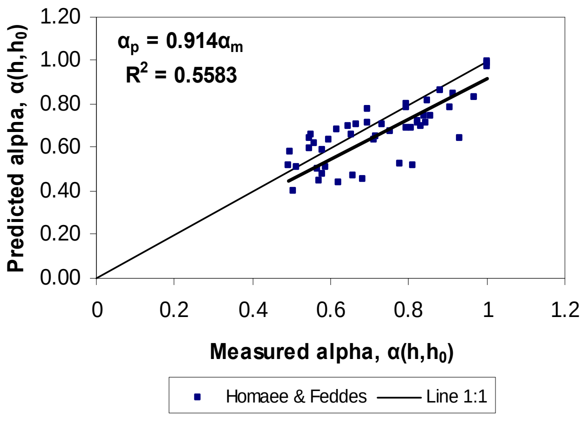

Figure 1. Relationship between measured and predicted water uptake reduction coefficients, α (h,h_o) by Homaee and Feddes (1999) method.

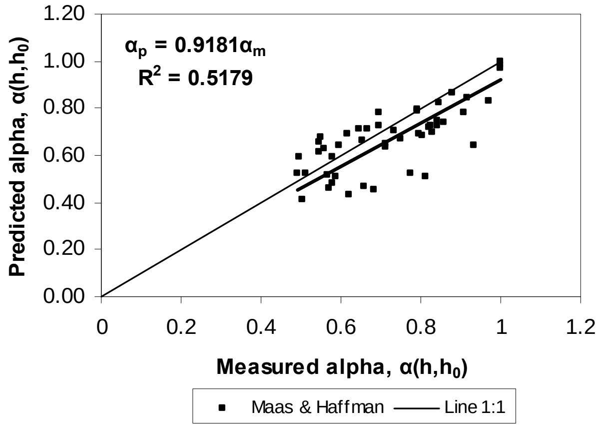

Figure 2. Relationship between measured and predicted water uptake reduction coefficients, $\alpha(h,h_o)$ by Maas and Hoffman (1977) method.

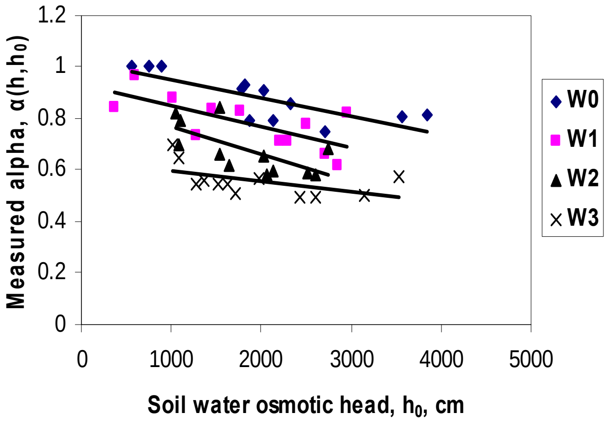

Figure 3. Relationship between measured water uptake reduction coefficient, $\alpha(h,h_o)$ and soil water osmotic head at different irrigation intervals: (W_0) 2-day, (W_1) 4-day, (W_2) 6-day, (W_3) 8-day.

Variation of root-water uptake coefficient with matric head

Variation of root-water uptake coefficient as a function of soil matric head in different salinity levels is shown in Figure 4. Root-water uptake coefficient reduced by decreasing in soil matric head and soil osmotic head at salinity levels greater than S_0. The slopes of these relationships at different salinity levels are not statistically different. However, the values of α (h, h_o) were reduced at higher salinity levels.

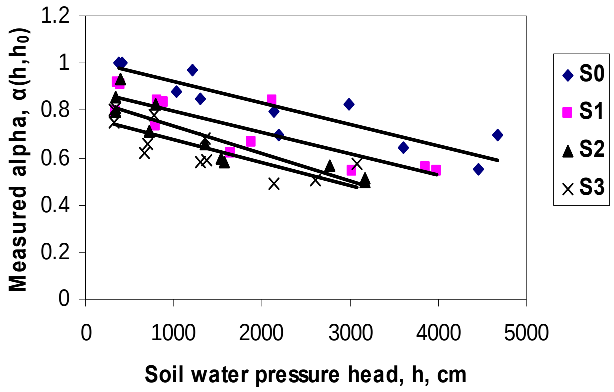

Figure 4. Relationship between measured water uptake reduction coefficient, α (h,h$_o$) and soil matric head at different irrigation water salinities: (S$_0$) 0.5 dS m^{-1}, (S$_1$) 1.7 dS m^{-1}, (S$_2$) 2.9 dS^{-1}, (S$_3$) 4.0 dS m^{-1}.

Yield prediction with root-water uptake coefficient

The flower yield was predicted by using Eqs (14a) and (14b) by using a value of 1.786 for K_y as determined by Sepaskhah and Yarami (2009). The relationships between the predicted saffron flower yield per pot by Eqs (14b) and (14a) and the measured values are shown in Figures 5 and 6, respectively. The values of α (h, h$_o$) used in Eq (14a) are those obtained by Homaee and Feddes (1999). The FAO method [Eq (14b)] resulted in poor estimation of saffron flower yield with coefficients of determination (R^2) of 0.22 and slope of 0.62. However, the Homaee and Feddes (1999) method [Eq (14a)] resulted in acceptable estimation of saffron flower yield with R^2 of 0.77 and slope of 0.75. Poor estimation of the FAO method was due to the fact that the calculated values of K_s from Eq (13) were negative for high irrigation intervals and high salinity levels (S_3W_1, S_3W_2, S_3W_3, S_2W_3, S_1W_2, S_1W_3, S_0W_2, and S_0W_3) that are not sound. Therefore, the estimated flower yields considered zero for the negative values.

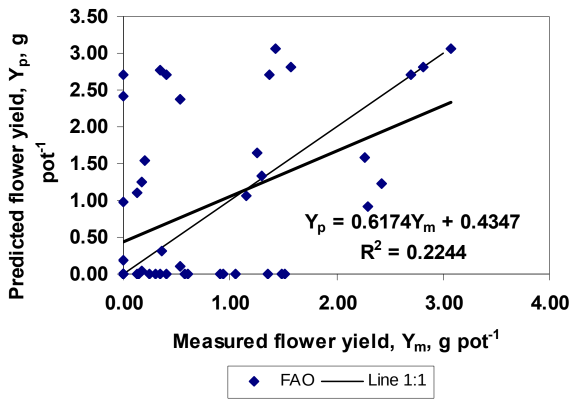

Figure 5. Relationship between measured and predicted flower yield by FAO method.

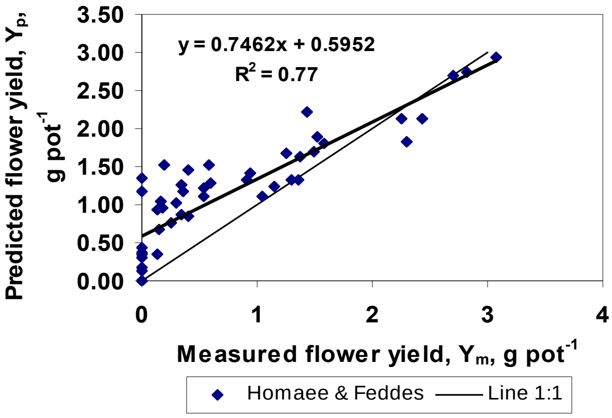

Figure 6. Relationship between measured and predicted flower yield by Homaee and Feddes (1999) method.

The relationships between the predicted saffron flower yields by Eqs (14a) and (14b) and the measured values were determined by regression analysis as follows:

(18) By Eq (14a): $Y_{fp} = 0.75\ Y_{fm} + 0.60$, R^2=0.77

(19) By Eq (14b): $Y_{fp} = 0.61\ Y_{fm} + 0.43$, R^2=0.22

where Y_{fp} and Y_{fm} are the predicted and measured saffron flower yields, respectively in, g pot^{-1} and R^2 is the coefficient of determination. The relationship obtained by Eq (14b) showed a low value of R^2 (0.22) that indicated a low precision for prediction. The F-test analysis showed that the slope of Eq (19) was statistically lower than 1.0 and the intercept was not statistically different from 0.0. The relationship obtained by Eq (14a) showed a higher value of R^2 (0.77) that indicated an acceptable precision for prediction. The F-test analysis showed that the slope of Eq (18) is not statistically different from 1.0, but the intercept was statistically higher than 0.0. Close examination of data in Figure 6 indicated that Eq (14a) over-predicted saffron flower yield at measured yields lower than about 1.0 g pot^{-1} that is about 40% of the control yield. This might be the reason for significant higher value of intercept than 0.0. Therefore, it is indicated that flower yield of saffron was predicted by Eq (14a) with an acceptable precision at salinity and water stress treatments with relative yield of greater than about 40%.

Conclusions

At every irrigation interval, the root-water uptake coefficient reduced as the soil osmotic head decreased at higher salinity levels. Furthermore, the values of α (h, h_o) were reduced at higher irrigation intervals. Root-water uptake coefficient was reduced by decreasing soil matric head and soil osmotic head at salinity levels greater than S_0. The results indicated that the additive and multiplicative functions for root-water uptake presented by van Genuchten (1987) [Eqs (3) and (4)] and Dirksen et al. (1993) equation [Eq (8)] were not suitable for prediction of root-water uptake coefficient of saffron to show the interaction effect of salinity and deficit irrigation on yield prediction. The Mass and Hoffman (1977) and Homaee and Feddes (1999) equations [Eqs (9) and (10)] were resulted acceptable estimation of α (h,h_o). Furthermore, saffron flower yield was predicted by using Homaee and Feddes (1999) equation and FAO method along with production function presented by Stewart et al. (1977). Results indicated that the FAO method did not predict the saffron flower yield properly specially in high irrigation intervals and high salinity levels, but the Homaee and Feddes (1999) method resulted in acceptable prediction of the saffron flower yield with a minimum error. Therefore, Homaee and Feddes (1999) equation is recommended for estimation of α (h, h_o) and flower yield of saffron. In this estimation, the values of threshold soil matric and osmotic heads for water uptake reduction are -709 and -522 cm, respectively. Further, the minimum soil matric and osmotic heads for water uptake inhibition are -34965 and -2603 cm, respectively. These values were used in Homaee and Feddes (1999) equation for estimation of α (h, h_o) and flower yield of saffron.

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