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Effect of irrigation interval and water salinity on growth of madder (*Rubina tinctorum* L.)

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Abstract

Madder (*Rubina tinctorum* L.) is mainly cultivated in central part of I.R. of Iran that is an arid and desert area with scarce and saline water resources. Its root is used as herbal medicine and food additives and its shoot (top) is used as forage crop. However, little is known about its salinity tolerance and soil water limits for growth. The objectives of the present study were to investigate the limits of irrigation water salinity and soil water content for growth inhibition of madder. Furthermore, two different models were studied to describe the root water uptake and top and root growth under salinity and water stresses in a pot experiment. Irrigation treatments consisted of three irrigation intervals (2, 5, and 8-day). The salinity treatments of the irrigation water were 0.5 (tap water), 7.5, 15.5, and 23.5 dS m^{-1}. It is concluded that the critical volumetric soil water content equivalent to soil matric head of -1462.0 cm for madder growth is lower than 0.23 cm^3 cm^{-3}. The coefficient of readily available water for madder is at least 0.6. Furthermore, the vegetative growth response factor of madder to water is 0.33 and 0.42 for shoot and root dry weight, respectively. There were no difference in shoot and root growth tolerance to soil salinity and irrigation water salinity at different water stress levels. Furthermore, the threshold values of soil salinity and irrigation water salinity are 17.0 and 11.6 dS m^{-1} for top growth, respectively, and 15.3 and 8.5 dS m^{-1} for root growth, respectively. The growth reduction per unit increase in soil salinity and irrigation water salinity for top growth are 2.0,3.7 % per dS m^{-1}, respectively. These values are 1.9, 3.1 % per dS m^{-1}, respectively for root growth. Therefore, top and root growth affected similarly by increasing the soil salinity and irrigation water salinity. It is indicated that the root water uptake coefficient (α) was predicted accurately by the used models. Furthermore, the estimated values of α accurately predicted the shoot dry weight successfully. However, Homaee and Feddes (1999) method is preferred for estimation of root dry weight.

Keywords: Matric head; Saline water; Soil salinity; Osmotic head; Critical soil water content; Iran

Introduction

The madder (*Rubina tinctorum* L.) is a perennial herbaceous plant (Gulhan et al., 1999). It is native to the Middle East region and is cultivated in south and southeast of Europe, Mediterranean area and central Asia (Derksen et al., 2002). It is used to be cultivated in northwest, central and south of I. R. of Iran. However, it is mainly cultivated in Yazd province in central region (I.R. of Iran) that is an arid and desert area with scarce and saline water resources. The madder tops are used as forage crop harvested in first and second year and its root is harvested in third year to be used as a dyer madder. Furthermore, its use as herbal medicine has been reported by Khalil et al. (2006) and Hazra et al. (2004) and as food additives by Tereda et al. (2004).

Effect of soil salinity with different types of salt on madder growth was investigated by Dashtakian (2000). The survival of madder is higher with sodium sulfate than that with sodium chloride as the main source of soil salinity (Dashtakian, 2000). The growth reduction per unit soil salinity under sodium sulfate is lower than that obtained under sodium chloride. Furthermore, it was reported that salinity effects occurred on vegetative growth but not on seed yield (Namjuyan et al., 1998).

The madder is planted in desert area in Iran with scarce water that is highly saline. However, little is known about the salinity tolerance of this crop. Furthermore, there are few information on madder crop water use under varying irrigation water management.

The objectives of this study were to investigate salinity tolerance and growth of madder under different irrigation water management levels. Furthermore, different models were studied to describe the root water uptake under different levels of salinity and water stresses to be used for shoot (top) and root dry matter prediction.

Materials and Methods

Field experiment

This research was conducted in a greenhouse at college of Agriculture, Shiraz University in year 2007. The soil was a loam collected from the top 20 cm layer and some of the physico-chemical properties of this soil are shown in Table 1. The soil was air-dried, crushed to pass through a 10-mm sieve. Forty eight plastic pots with 23.5 cm in height and 23 cm in diameter were filled with 6.5 kg of air-dried soil with a layer of gravel filter (2-4 mm gravel and 2 cm thick) at bottom. Holes were drilled on the bottom of pots for drainage. About 100 g of madder seeds pretreated with sulfuric acid with concentration of 90% for 25 minutes. Twenty pretreated seeds (local cultivar of Esmat) were planted at 3 cm depth in each pot on 8 April, 2007, and each pot irrigated with tap water (EC of 0.5 dS m^{-1}) to field capacity. After 2 weeks, seedlings were thinned to 10 plants per pot and after 4 weeks, they were thinned to 5 plants per pot. During this period, the soil water kept at field capacity by irrigation with tap water. The pots were subjected to experimental treatments after the last thinning.

Irrigation treatments consisted of three irrigation intervals (W_0, W_1, and W_2) 2-, 5-, and 8-day intervals. The salinity treatments of the irrigation water were 0.5 (tap water as control), 7.5, 15.5, and 23.5 dS m^{-1} (S_0, S_1, S_2, and S_3) obtained by the addition of NaCl and $CaCl_2$ to the tap water with equal equivalent proportion. The experimental layout was a 3×4 factorial arrangement with four replications. The amount of water for each irrigation was determined by weighting the pots, and raising the soil water content to the field capacity. Thirty percent more water was applied as leaching requirement to control the salt accumulation in pots. The chemical analysis of saline irrigation water is shown in Table 2.

The maximum and minimum air temperatures in the greenhouse were 34±6 and 12±6˚C, respectively.

Table 1. Physico-chemical properties of the soil used in the experiment.

Physical property		Chemical property	
Sand (%)	17	Ca (meq l^{-1})	3.80
Silt (%)	47	Cl (meq l^{-1})	1.90
Clay (%)	36	Na (meql^{-1})	1.50
Field capacity (cm^3 cm^{-3})	0.35	SO_4 (meq l^{-1})	1.90
Permanent wilting point (cm^3 cm^{-3})	0.15	Mg (meq l^{-1})	1.70
Bulk density (g cm^{-3})	1.29	HCO_3 (meq l^{-1})	2.60
		EC (dS m^{-1})	0.57

Table 2. Chemical analysis of the saline irrigation water used in the experiment.

EC dS m^{-1}	pH	Cl meq l^{-1}	Na meq l^{-1}	Ca meq l^{-1}	HCO_3 meq l^{-1}
0.5	8.2	7.1	3.5	3.1	2.7
7.5	7.9	228.2	163.0	56.0	7.7
15.5	7.6	636.7	454.8	185.0	6.5
23.5	7.5	976.6	751.2	193.2	4.1

Soil samples were used to determine the soil water retention curve by hanging water column and pressure plate apparatus. The soil water retention equation is shown as follows:

$$\theta = 0.1 + 0.40(1 + |0.015 \times h|^{1.36})^{-0.262} \qquad (1)$$

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

Before each irrigation, soil water content in pots were measured by weighing the pots. Drainage water was collected six times during the growing season. Electrical conductivity was determined in the drainage water during the growing season. Osmotic head of the drainage water as soil solution was estimated by the following equation (Richards, 1954):

$$h_o = -360 \times EC_{ss} \qquad (2)$$

where h_o is the osmotic potential in cm and EC_{ss} is the soil solution salinity in dS m^{-1}. Soil water content before each irrigation converted to soil water matric head by using the soil water retention curve [Eq. (1)].

The plants harvested on September 21, 2007. The harvested plant tops dried in oven under 65 ˚C for 48 h and weighed. At harvest, the soil in pots washed to separate the roots. The washed roots dried in oven with 65˚C for 48 h, and weighed. The results were subjected to statistical analysis and means were compared by the Duncan multiple range test. Chloride and sodium content of plant top were determined according to procedures proposed by Chapman and Pratt (1961).

Water uptake models

Water flow in unsaturated soils described with Richards equation (Belmans et al., 1983). Including the root extraction term *S*, it is as follows:

$$\frac{\partial\theta}{\partial t}=C(h)\frac{\partial h}{\partial t}=\frac{\partial}{\partial Z}(K(h)\frac{\partial h}{\partial Z}+K(h))-S \qquad (3)$$

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 of the soil water retention curve ($d\theta/dh$), 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:

$$S=\alpha(h.h_0)S_{\max} \qquad (4)$$

Where $S_{\max}$ is the maximum water uptake rate and α (h,h_0) is a dimensionless function of pressure and osmotic head. Maas and Hoffman (1977) proposed the following equation for the macroscopic reduction function:

$$\alpha(h,h_0)=\frac{h-h_4}{h_3-h_4}\times[1-\frac{a}{360}(h_0^*-h_0)] \qquad (5)$$

Where h_3 is the soil water pressure head threshold value, h_4 is the soil water pressure head at wilting, h_o^* is the osmotic pressure head at threshold soil salinity, h_o is the osmotic pressure head, and a is the yield reduction percent per unit salinity ($dS\ m^{-1}$). This equation is valid for $h_o \le h_o^*$ and $(h_4-h_o) \le h \le h_3$, respectively.

Homaee and Feddes (1999) proposed another equation that is a combination of linear and non-linear and differs conceptually from additive and multiplicative theories. Further assumption is that each dS m^{-1} salinity beyond the threshold value (EC^*) shifts the wilting point 360 cm to the left. In this method, the reduction function for water uptake is as follows:

$$\alpha(h,h_0)=\frac{h-(h_4-h_0)}{h_3-(h_4-h_0)}\left[1-\frac{a}{360}(h_0^*-h_0)\right] \qquad (6)$$

Root-water uptake coefficient (α) is relative transpiration that obtained from ratio of the actual transpiration to the potential transpiration. In this study it is assumed that the relative transpiration is equal the relative evapotranspiration. Therefore, to determine α, the actual evapotranspiration (irrigation intervals of 5 and 8-day) was divided by the potential evapotranspiration (irrigation interval of 2-day) and the results were taken equivalent to the root-water uptake coefficient.

Yield models

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

$$\frac{Y_a}{Y_m}=1-K_y\left[1-\frac{ET_{c-adj}}{ET_p}\right] \qquad (7)$$

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 at water stress, ET_p is the crop evapotranspiration for standard condition (no water stress) mm d^{-1} and ET_{c-adj} is the adjusted crop evapotranspiration mm d^{-1} that is calculated as follows:

$$ET_{c-adj} = K_s \times ET_p \qquad (8)$$

in which K_s is the transpiration reduction factor and dependent on available soil water that is vary between 0-1 and under salinity and water stress condition proposed (Allen et al., 1998):

$$K_s = \left[1 - \frac{b}{K_y 100}\left(EC_e - EC_{e-threshold}\right)\right] \times \left[\frac{TAW - Dr}{TAW - RAW}\right] \qquad (9)$$

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), *p* is the fraction of *TAW* that a crop can extract from the root zone without suffering water stress. Therefore, relative yield under water and salinity stress proposed as follows:

$$\frac{Y_a}{Y_m} = 1 - K_y\left[1 - \frac{\alpha(h, h_0) ET_p}{ET_p}\right] \qquad (10a)$$

$$\frac{Y_a}{Y_m} = 1 - K_y\left[1 - \frac{K_s ET_p}{ET_p}\right] \qquad (10b)$$

Application of equation (10b) should usually be restricted to $EC_e < EC_{e\text{-}threshold} + 50/b$ and it predicts Y_a=0 at K_s=0. Futhermore, 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 (8) is replaced by $\alpha(h, h_0)$ Eq (10a) is obtained that is a different method for calculation of $ET_{c\text{-}adj}$. Then, Eq (10a) is used to estimate relative yield and with knowing the maximum yield, Y_m, the value of actual yield, Y_a, is estimated.

Results and Discussion

Irrigation and salinity effects

Top dry weight

At different irrigation intervals, the top dry weights were statistically similar (p=0.05) at water salinity levels of 0.5 and 7.5 dS m^{-1}, however, they were statistically different (p=0.05) with those obtained at water salinity levels of 15.5 and 23.5 dS m^{-1} (Table 3). Furthermore, top dry weights were statistically similar at water salinity levels of 15.5 and 23.5 dS m^{-1}. However, the main effect of water salinity on top dry weight reduction was significant between water salinity levels of 7.5, 15.5, and 23.5 dS m^{-1}. This indicates that there is a weak interaction between water salinity level and irrigation intervals with a probability level (p value) of 0.17 as obtained by statistical analysis. This weak interaction effect is shown in a small decrease in top dry weight as the irrigation interval increased at water salinity levels of 0.5, 7.5, and 15.5 dS m^{-1}. However, top dry weight showed a small but not statistically significant increase as the irrigation interval increased at water salinity level of 23.5 dS m^{-1}. This might be due to the fact that less chloride and sodium is absorbed by plant shoot (Table 4) at water salinity level of 23.5 dS m^{-1} and irrigation interval of 8-day, therefore, top dry weight showed a rising trend (Table 3).

Table 3. Top dry weight (g pot^{-1}) in different levels of salinity and irrigation intervals.

Salinity levels dS m^{-1}	Irrigation intervals, day			
	2 (W_0)	5 (W_1)	8 (W_2)	Mean
0.5 (S_0)	6. 825a*	5.775b	6.025ab	6.208A
7.5 (S_1)	6.201ab	5.525b	5.800b	5.842A
15.5 (S_2)	1.901c	1.725cd	1.725cd	1.783B
23.5 (S_3)	0.550ef	1.000de	1.000de	0.850C
Mean	3.869A	3.506A	3.637A	

*Means followed by the same letter in each column and rows are not significantly different at 5% level of probability by Duncan multiple range test.

Table 4. Top Cl and Na contents (%) in different levels of salinity and irrigation intervals.

Salinity levels dS m^{-1}	Irrigation intervals, day		
	2 (W_0)	5 (W_1)	8 (W_2)
		----Cl----	
0.5 (S_0)	2.4	2.1	1.9
7.5 (S_1)	3.1	2.9	2.8
15.5 (S_2)	5.6	5.1	5.2
23.5(S_3)	8.4	7.8	7.3
		----Na---	
0.5 (S_0)	1.2	1.05	0.9
7.5 (S_1)	2.6	2.2	2.15
25.5 (S_2)	4.5	3.9	3.9
23.5(S_3)	7.6	6.8	6.5

Top dry weight was correlated to the top chloride and sodium content by regression analysis as follows:

$(Y)_{top}$=8.23-1.0$(Cl)_{top}$, R^2=0.89 (11)

$(Y)_{top}$=7.21-0.98$(Na)_{top}$, R^2=0.84 (12)

Where Y_{top} is the top dry weight in g pot^{-1}, Cl_{top} is the top chloride content in %, and Na_{top} is the top sodium content in %. Equations (11) and (12) indicate that top dry weight reduction is affected equally by accumulation of *Cl* and *Na* in plant top due to similar values of slope in these equations.

Root dry weight

Similar results to shoot dry weight were obtained for root dry weight (Table 5). However, there is no significant interaction effect between salinity levels of irrigation water and irrigation intervals. At salinity level above 7.5 dS m^{-1}, there were statistically significant reduction in root dry weight.

Table 5. Root dry weight (g pot^{-1}) in different levels of salinity and irrigation intervals.

Salinity levels dS m^{-1}	Irrigation intervals, day			
	2 (W_0)	5 (W_1)	8 (W_2)	Mean
0.5 (S_0)	1.550a*	1.400a	1.475a	1.183A
7.5 (S_1)	1.450a	1.575a	1.550a	1.266A
15.5 (S_2)	0.350bc	0.575b	0.600b	0.500B
23.5(S_3)	0.125c	0.125c	0.200c	0.150C
Mean	0.713A	0.750A	0.869A	

*Means followed by the same letter in each column and rows are not significantly different at 5% level of probability by Duncan multiple range test.

Evapotranspiration

At different irrigation intervals, the evapotranspiration (ET) statistically were similar. However, there was a slight decrease in its values especially at salinity levels of 0.5 to 15.5 dS m^{-1} (Table 6). Statistically significant decrease in ET occurred at salinity levels of irrigation water higher than 7.5 dS m^{-1}. Furthermore, no significant interaction between salinity level and intervals of irrigation was obtained.

Table 6. Seasonal evapotranspiration (mm) in different levels of salinity and irrigation intervals.

Salinity levels dS m^{-1}	Irrigation intervals, day			
	2 (W_0)	5 (W_1)	8 (W_2)	Mean
0.5 (S_0)	357.9a*	341.2a	323.5ab	340.8A
7.5 (S_1)	271.5ab	279.3ab	234.8bc	261.9A
15.5 (S_2)	155.6cd	153.6cd	130.3d	146.5B
23.5(S_3)	81.3d	74.2d	88.1d	81.2B
Mean	217.0A	212.1A	194.2A	

*Means followed by the same letter in each column and rows are not significantly different at 5% level of probability by Duncan multiple range test.

Relationship between relative top dry weight (relative to those obtained at irrigation interval of 2-day) for water salinity level of 0.5 dS m^{-1} determined by regression analysis as follows:

$(1\text{-}Y_a/Y_m)_{top}$=0.33$(1\text{-}ET_a/ET_m)$, R^2=0.68 (13)

$(1\text{-}Y_a/Y_m)_{root}$=0.42$(1\text{-}ET_a/ET_m)$, R^2=0.61 (14)

Where $(1\text{-}Y_a/Y_m)_{top}$ and $(1\text{-}Y_a/Y_m)_{root}$ are the relative top and root dry weight reduction and $(1\text{-}ET_a/ET_m)$ is the relative evapotranspiration reduction. Coefficients of Eq. (13), and (14) are the growth response factor to water for top and root dry weight, respectively. These values show that there is not pronounce differences in the top and root response factors to water.

Soil water content

Mean volumetric soil water contents before irrigation events are shown in Table 7. There is no statistical difference (p=0.05) between soil water content at different salinity levels of irrigation water. However, it is statistically lower at irrigation interval of 8-day. This is most pronounce at salinity bevel of 0.5 dS m^{-1} with the lowest volumetric soil water content of 0.23 cm^3 cm^{-3}. This volumetric soil water content is equivalent to soil matric head of -1462.0 cm according to Eq. (1).

According to Table 1, the soil water contents at field capacity and permanent wilting point are 0.35 and 0.15 cm^3 cm^{-3}, respectively. Therefore, by considering 0.23 cm^3 cm^{-3} for critical value of soil water content (Doorenbos and Pruitt, 1977), the coefficient of readily available water is as follows:

$p=RAW/TAW= (\theta_{fc}-\theta_{p})/(\theta_{fc}-\theta_{pwp})$ (15)

p= (0.35-0.23)/(0.35-0.15)=0.6

Table 7. Seasonal mean soil volumetric water content (cm^3 cm^{-3}) in different levels of salinity and irrigation intervals.

Salinity levels dS m^{-1}	Irrigation intervals, day			
	2 (W_0)	5 (W_1)	8 (W_2)	Mean
0.5 (S_0)	0.33ab*	0.285abc	0.232c	0.282A
7.5 (S_1)	0.33ab	0.290abc	0.247bc	0.289A
15.5 (S_2)	0.34a	0.300abc	0.247bc	0.295A
23.5(S_3)	0.34a	0.323ab	0.253abc	0.253A
Mean	0.335A	0.298AB	0.244B	

*Means followed by the same letter in each column and rows are not significantly different at 5% level of probability by Duncan multiple range test.

Where *RAW* is the readily available water, *TAW* is the total available water, θ_{fc} is the field capacity, θ_{pwp} is the permanent wilting point, θ_p is the critical water content, and *p* is the coefficient of readily available water. Therefore, the value of *p* is 0.6 for madder crop. Furthermore, the soil matric head for permanent wilting point is -22105.0 cm according to Eq. (1).

Growth function-soil salinity

Relationships between relative top and root dry weights and salinity of the soil drainage water determined by regression analysis as follows and are presented in Figures 1 and 2:

$(Y_a/Y_m)_{top}=1-0.020(EC_{ss}-17.0)$, $R^2=0.94$ (16)

$(Y_a/Y_m)_{root}=1-0.019(EC_{ss}-15.3)$, $R^2=0.80$ (17)

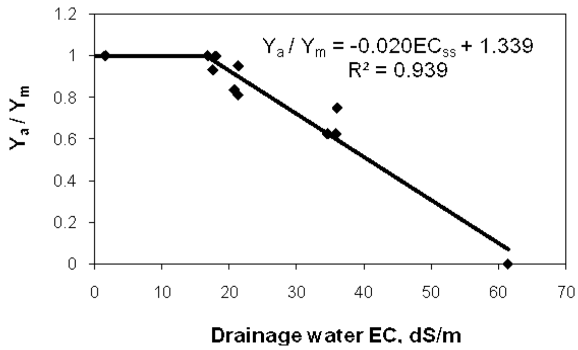

Figure 1. Relationship between relative top dry weight and salinity of drainage water.

Where $(Y_a/Y_m)_{top}$ and $(Y_a/Y_m)_{root}$ are the relative top and root dry weights, and EC_{ss} is the salinity of the soil drainage water in dS m^{-1}. The threshold of EC_{ss} and the growth reduction coefficient for top dry weight is 17.0 dS m^{-1} and 2.0 % per unit salinity increase, respectively. Similar equations to Eq (16) were obtained for each irrigation treatments; however, their threshold values for EC_{ss} and growth reduction coefficients were not different. Therefore, they were combined in one equation as Eq (16). The value of osmotic head equivalent to the threshold EC_{ss} is -5710.0 cm according to Eq. (2). According to Eq. (16), the salinity of drainage water for zero relative top dry weight is 67.0 dS m^{-1} and the equivalent osmotic head is -22219.0 cm.

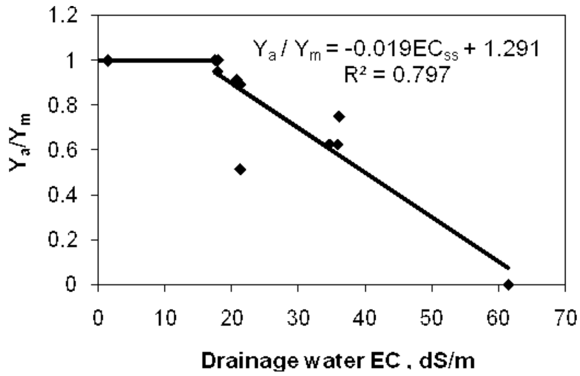

Figure 2. Relationship between relative root dry weight and salinity of drainage water.

The threshold EC_{ss} for root dry weight is 15.3 dS m^{-1}, and it is lower than that obtained for shoot dry weight. The growth reduction coefficient for root dry weight is 1.9 % per unit increase in soil salinity and it is similar to that obtained for shoot dry weight (2.0 % per unit salinity). Similar equations to Eq (17) were obtained for each irrigation treatments; however, their threshold values for EC_{ss} and growth reduction coefficients were not different. Therefore, they were combined in one equation as Eq (17). Based on Eq (2), the value of osmotic head equivalent to the threshold EC_{ss} is -4382.0 cm. According to Eq. (17), the salinity of drainage water for zero relative root dry weight is 67.9 dS m^{-1} and the equivalent osmotic head is -22204.0 cm.

Growth function-water salinity

Relationships between relative top and root dry weight and salinity of irrigation water determined by regression analysis as follows (Figures 3 and 4):

$$(Y_a/Y_m)_{top}=1-0.037(EC_{iw}-11.6), \quad R^2=0.78 \qquad (18)$$

$$(Y_a/Y_m)_{root}=1-0.031(EC_{iw}-8.5), \quad R^2=0.70 \qquad (19)$$

where EC_{iw} is the salinity of irrigation water in dS m^{-1}. The values of 11.6 and 8.5 are the threshold EC_{iw} for top and root dry weight, respectively. The coefficients in Eqs. (18), and (19) are very close together for top and root dry weights (3.7 and 3.1 % per unit salinity, dS m^{-1}, respectively). Again, growth reduction rates are almost similar for top and root dry weights. However, the threshold value of EC_{iw} is lower for root dry weight (8.5 dS m^{-1}) than that obtained for top dry weight (11.6 dS $^{-1}$). According to the values of threshold and growth reduction coefficient, it is indicated that madder plant is highly tolerant to salinity and its tolerance is even higher than barley with threshold and growth reduction coefficient of 8.0 dS m^{-1} and 5.0 % per unit salinity, respectively, as listed by Maas (1990).

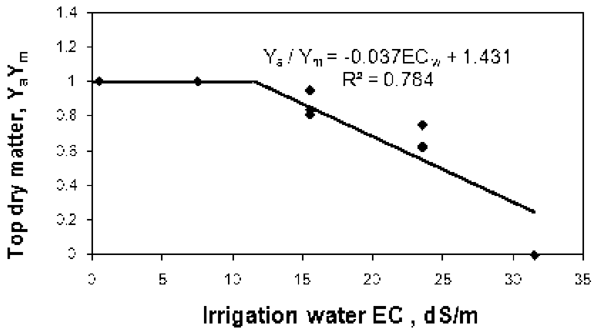

Figure 3. Relationship between relative top dry weight and salinity of irrigation water.

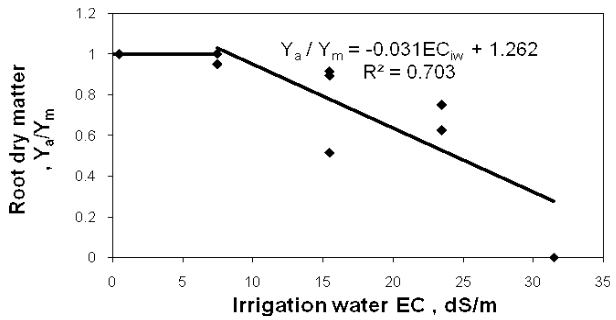

Figure 4. Relationship between relative root dry weight and salinity of irrigation water.

Root-water uptake coefficient

The root-water uptake coefficients (α) were estimated by Eqs (5), and (6) proposed by different investigators. In these estimations, the corresponding values of soil matric and osmotic heads were used as presented in Table 8. The measured and estimated mean values of root-water uptake coefficients by different methods illustrated in Figures 5 and 6.

Table 8. Soil matric and osmotic potentials at different points in the range of their variations.

Potential	Different point	Potential value, cm
Matric	h_3	-1540.0
	h_{max}	-22105.0
Osmotic	h_o^*	-5710.0
	h_{omax}	-22219.0
Growth reduction coefficient (% per dS m^{-1})	a	2.0

The estimated values of α by Homaee and Feddes (1999) [Eq (6)] Maas and Hoffman (1977) [Eq. (5)] are closed to those of measured values (Figures 5 and 6). Relationship between the predicted and measured values of α was determined by linear regression analysis. The statistical results are shown in Table 9. The slopes of linear relationships between the estimated α(h, h_o) by multiplicative functions (Maas and Hoffman, 1977) and a combination function (Homaee and Feddes, 1999) and the measured values are statistically close to 1.0, and their intercepts were statistically zero. Therefore, these functions are appropriate for estimation of α(h, h_o).

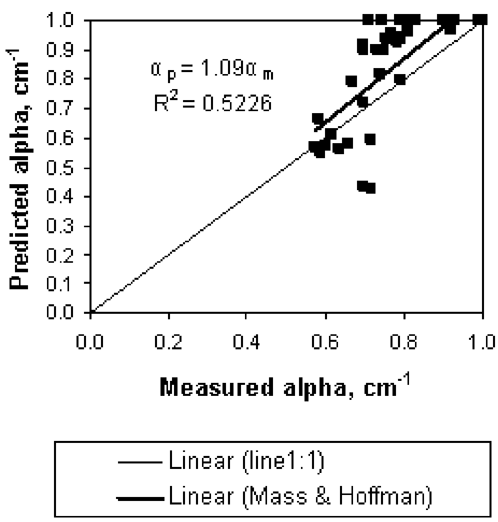

Figure 5. Relationship between measured and predicted values of alfa by Maas and Hoffman (1977) (Bold line) and 1:1 line (thin line).

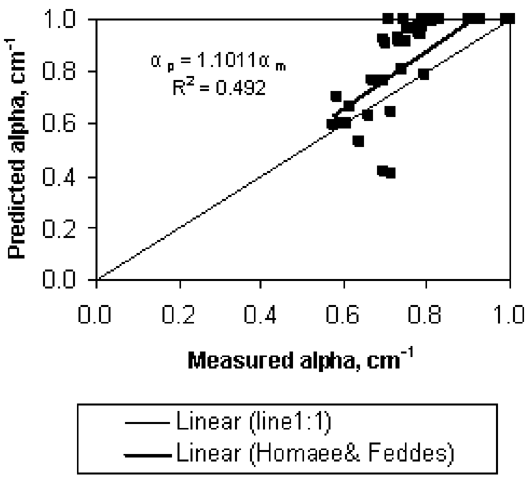

Figure 6. Relationship between measured and predicted values of alfa by Homaee and Feddes(1999) (Bold line) and 1:1 line (thin line).

Table 9. The results of F-test analysis for comparison between predicted values of water uptake (α_p) and measured values (α_m).

Equation number	Linear equation	R^2	n	SE	P	Slope	Intercept
						Probability level	
						5%	
Eqn (5)	α_p=1.09 α_m	0.52	48	0.124	5.16E-09	NS	-
Eqn (6)	α_p =1.01 α_m	0.49	48	0.124	2.76E-08	NS	-

Top and root dry weight prediction with root-water uptake coefficient

The top and root dry weight was predicted by using Eqs (10a) and (10b) and a value of 0.33 and 0.42 for K_y for top and root dry weight as determined by Eqs. (13) and (14). The relationships between the predicted top and root dry weight by Eqs (10b) and (10a) and the measured values are shown in Figures 7 to 10, respectively. The values of α used in Eq (10a) are those obtained by Homaee and Feddes (1999). The FAO method [Eq (10b)] used the values of K_s calculated by Eq. (9). Relationships between predicted and measured shoot and root dry weights determined by regression analysis. Results presented in Table 10. The Homaee and Feddes (1999) method [Eq (10a)] and the FAO method [Eq. (10b)] resulted in good estimation of shoot dry weight with R^2 of 0.94 and 0.89, and slopes of 0.94 and 0.93, respectively (Table 10). Similar relationships between measured and predicted root dry weights were obtained for root dry weight by different prediction models. However, higher value of R^2 was obtained for FAO method [Eq (10b)] but its slope was statistically different from 1.0 (p=0.01). Therefore, it is indicated that Hommaee and Feddes (1999) method is preferred for root dry weight estimation.

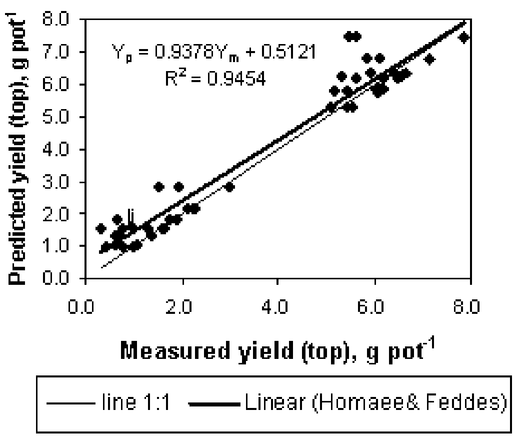

Figure 7. Relationship between predicted and measured top dry weight by Hommaee and Feddes (1999) [Eq. (10a)].

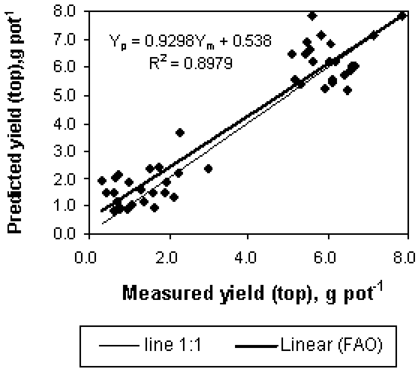

Figure 8. Relationship between predicted and measured top dry weight FAO method [Eq. (10b)].

Table 10. The results of F-test analysis for comparison between measured and predicted values of shoot and root dry weight by different prediction models.

Equation number	Linear equation	R^2	n	SE	P	Slope	Intercept
						Probability level 1%	
Eq (10a) Shoot	Y_p=0.94Y_m+0.51	0.94	48	0.012	1.10E-30	NS	S
Eq (10b) Shoot	Y_p =0.93Y_m+0.54	0.89	48	0.017	1.94E-24	NS	NS
Eq (10a) Root	Y_p=0.89Y_m	0.86	48	0.005	5.32E-22	NS	-
Eq (10b) Root	Y_p=0.87Y_m	0.95	48	0.003	1.43E-33	S	-

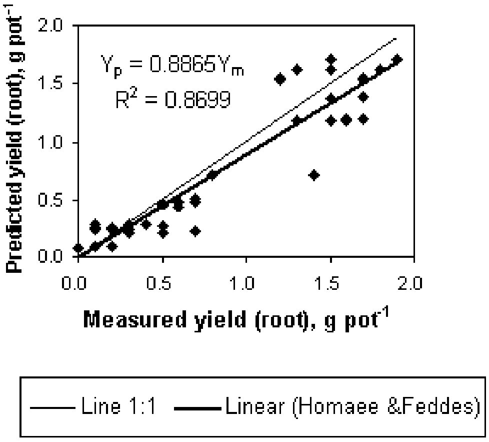

Figure 9. Relationship between predicted and measured root dry weight by Homaee and Feddes (1999) method [Eq. (10a)].

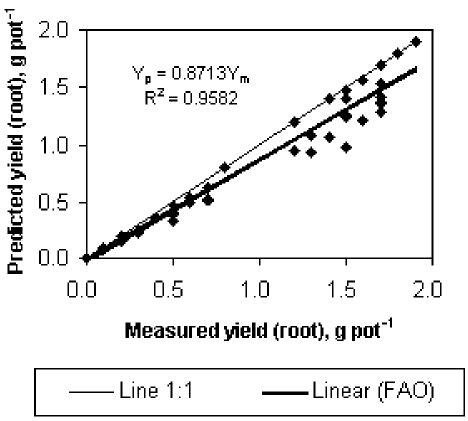

Figure 10. Relationship between predicted and measured root dry weight by FAO method (Eq. (10b)].

Conclusions

It is concluded that the critical volumetric soil water content for shoot and root growth is lower than 0.23 cm^3 cm^{-3} that is equivalent to soil matric head of -1462.0 cm. The coefficient of readily available water for madder is at least 0.6. Furthermore, the vegetative growth response factor of madder to water is 0.33 and 0.42 for top and root, respectively.

There was no difference between shoot and root growth tolerance to soil salinity and irrigation water salinity at different water stress levels. Furthermore, the threshold values of soil salinity and irrigation water salinity are 17.0 and 11.6 dS m^{-1} for top growth, respectively, and 15.3 and 8.5 dS m^{-1} for root growth, respectively. The growth reduction per unit increase in soil salinity and irrigation water salinity for top growth are 2.0 and 3.7 % per dS m^{-1}, respectively. These values are 1.9 and 3.1 % per dS m^{-1}, respectively for root growth. Therefore, shoot and root growth affected similarly by increasing the soil salinity and irrigation water salinity.

It is also concluded that madder can be planted in areas with soil salinity levels greater than 15.0 dS m^{-1} and irrigation water with salinity level greater than 8.5 dS m^{-1}.

It is indicated that the root water uptake coefficient (α) is predicted accurately by Homaee and Feddes (1999) and Maas and Hoffman (1977) methods. Furthermore, the estimated values of α by these methods accurately predicted the shoot dry weight successfully. However, Homaee and Feddes (1999) method is preferred for estimation of root dry weight.

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