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Rice Yield Modeling under Salinity and Water Stress Conditions using an Appropriate Macroscopic Root Water Uptake Equation

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Abstract: The objectives of this study were to evaluate the application of different macroscopic root water extraction models for prediction of rice grain yield based on data obtained in a greenhouse experiment. In this experiment, the irrigation treatments were continuous flooding (control), intermittent flooding (1- and 2-day intervals) and the salinity levels of irrigation water were 0.6 (control), 1.5, 3, 4.5 and 6 dS m^{-1} in the year of 2005 and 0.6 (control), 1.5, 2.5, 3.5 and 4.5 dS m^{-1} in the year of 2006. A local cultivar (Ghasrodashty/Komphiroozy) was planted in pots under greenhouse condition during years 2005 and 2006. Grain yield and evapotranspiration at different treatments were determined. The effect of salinity and water stress on root-water uptake coefficient was determined by FAO and Homaee and Feddes methods and grain yield was predicted by production functions. The FAO method did not predict the interaction effects of salinity and water stress on reduction of water uptake coefficient especially at high salinity levels, while the Homaee and Feddes method predicted properly the effects of salinity and water stress on root-water uptake coefficient. Further, yield was predicted by using the root-water uptake coefficient suggested by FAO and Homaee and Feddes methods. The results indicated that the FAO method did not predict the yield properly especially in continuous flooding and salinity level of more than threshold values, but the Homaee and Feddes method predicted the grain yield with minimum error.

Key words: Deficit irrigation, production function, matric potential, osmotic potential

INTRODUCTION

Rice (*Oryza sativa* L.) is one of the major food grains for more than half of the world population and provides more than 80% of the daily calories for the consumers (Gallagher, 1984). Therefore, its production is vital to feed the ever growing population. Two important limitations for crop production in arid and semi-arid regions are water shortage and poor quality. Different methods of water management are used to cope with water shortage (Pirmoradian and Sepaskhah, 2007; Sepaskhah and Ghasemi, 2008). Rice growth and production models are often used to manage the water and salinity stress on rice production. In these models root water uptake coefficient is used (Feddes *et al*., 1978). Both salinity and water stress reduce root water uptake. Therefore, under water salinity and shortage conditions soil water is less available to plant. Rice is faced to salt and water stress in arid and semi-arid areas in southern part of Islamic Republic of Iran. Furthermore, crop evapotranspiration depletes the soil water content and reduces the matric and osmotic potential of the soil solution that result in root water uptake reduction.

Microscopic and macroscopic extraction approaches are available to quantify the root water uptake. The macroscopic approach is readily used by many investigators (Feddes *et al*., 1978) that defines the extraction term as the ratio of actual transpiration under stressed conditions to transpiration under non-stressed conditions. This ratio is quantified by the so-called water uptake reduction function. In the macroscopic models salinity conditions were not considered. Therefore, Van Genochten (1987) and Dirksen *et al*. (1993) used different nonlinear osmotic head-dependent reduction functions in Feddes *et al*. (1978) model as multiplicative water uptake reduction function. Recently, Homaee and Feddes (1999), Homaee *et al*. (2002) proposed linear reduction functions is neither additive nor multiplicative, but were assumed both the intercept and slope of the reduction function increased with salinity. These models were evaluated for saffron yield prediction by Sepaskhah and Yarami (2010) and it was indicated that Homaee and Feddes equation is preferable for estimation of root water uptake coefficient and flower yield of saffron.

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

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MATERIALS AND METHODS

Theory: Richards (1931) described the water flow in unsaturated soils including the root extraction term S, 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 the time (T), C the differential soil water capacity (L^{-1}) which 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 ($L^3/L/^3/T$) that determine:

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

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

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

where, h_{50} is the soil water pressure head at which $\alpha(h)$ is reduced by 0.50, a_1 and a_2 is coefficients that not yet defined either physically and the value is unit and p is an empirical parameter, the value of p was found to be about 3 when, the S-shaped function was applied to salinity stress data. The multiplicative water uptake reduction function suggested by Van Genochten (1987), Dirksen *et al.* (1993) and Homaee and Feddes (1999). The multiplicative reduction function (Van Genochten, 1987) is as follows:

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

where, h_{o50} is the soil salinity at which water uptake is reduced by 0.50. Homaee and Feddes (1999) proposed the following equation for the combined stresses:

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

where, h_{max} and h_{0max} (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, α_{01} and α_{02} is the relative transpiration at h_{max} and h_{0max} and p_1 and p_2 are defined as follows:

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

$$p_2 = \frac{h_{omax}}{h_{omax} - h_o^*} \tag{7}$$

Dirksen *et al.* (1993) described the multiplicative water uptake reduction function as follows:

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

Furthermore, Maas and Hoffman (1977) described the water uptake reduction function as follows:

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

Homaee and Feddes (1999) proposed the other equations that is a combination of linear and non-linear functions 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 per unit increase in salinity, therefore, reduction function of water uptake, α, is as follows:

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

where, h_3 is the soil water pressure head threshold value and h_4 is the soil water pressure head at wilting. This equation is valid for $h_o = h_o$* and $(h_4\text{-}h_o) = h = h_3$, respectively.

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

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

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

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

where, 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 was proposed by Allen *et al.* (1998) as follows:

$$K_s = \left[1 - \frac{b}{K_y 100}(EC_e - EC_{e-threshold})\right] \times \left[\frac{TAW - Dr}{TAW - RAW}\right] \tag{13}$$

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), 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 can be estimated by the following equations:

$$\frac{Y_a}{Y_m} = 1 - K_y\left[1 - \frac{ET_{c-adj}}{ET_p}\right] \tag{14}$$

$$\frac{Y_a}{Y_m} = 1 - K_y\left[1 - \frac{\alpha(h, h_0)ET_p}{ET_p}\right] \tag{15}$$

$$\frac{Y_a}{Y_m} = 1 - K_y\left[1 - \frac{K_s ET_p}{ET_p}\right] \tag{16}$$

Application of Eq. 16 should usually be restricted to $EC_e < EC_{e\text{-threshold}} + 50/b$ and it predicts $Y_a = 0$ 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.

When K_s in Eq. 12 is replaced by $\alpha(h, h_0)$, Eq. 15 is obtained that is a different method for calculation of $ET_{c\text{-adj}}$. Then, Eq. 15 is used to estimate relative yield and with knowing the maximum yield, Y_m, the value of actual yield, Y_a, is estimated.

Method: This study was carried out in a greenhouse at College of Agriculture, Shiraz University in years 2005 and 2006. The soil from top 20 cm layer of a rice planting area (Kooshkak, Fars province) with a silty clay texture was used. Some of the physico-chemical properties of this soil are shown in Table 1. The crushed air-dried soil was passed through a 2 mm sieve. An amount of 8.25 kg of this sieved soil was filled in plastic pots with 23.5 cm of height and 23 cm of diameter. Pots were planted with 25 seeds (local cultivar of Kamphiroozi/Ghasrodashti) in each pot on 18 and 27 April, 2005 and 2006, respectively and tap water was used to irrigate each pot to field capacity. Pots were fertilized with nitrogen and phosphorous uniformly at the rate of 163 mg kg^{-1} soil of ammonium nitrate (equivalent to 120 kg ha^{-1} N) and 51.6 mg kg^{-1} soil of triple superphosphate [$Ca(H_2PO_4)_2$] (equivalent to 50 kg ha^{-1} P), respectively. Seedlings were thinned to 15 and 10 per pot and after 2 and 4 weeks, respectively. After second thinning, the irrigation and salinity treatments initiated. Three irrigation treatments consisted of continuous flooding, intermittent flooding with 1 day interval and intermittent flooding with 2 day interval. A flexible drain tube was connected to the bottom end of pot wall for water drainage for intermittent irrigation treatments. These tubes were closed for continuous flood irrigation treatment. A 3 cm of standing water on the soil surface of the continuous flood irrigation was kept by daily water application. In intermittent irrigation treatments water was applied 1- and 2-day after the standing water disappeared. The amount of applied water in these treatments was the sum of water required to raise the soil water to saturation and a standing water depth of 3 cm.

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

Physical property	Values	Chemical property	Values
Sand (%)	5.00	Ca (mg L^{-1})	176.30
Silt (%)	49.00	Cl (mg L^{-1})	35.50
Clay (%)	46.00	Na (mg L^{-1})	5.57
Field capacity (cm^3 cm^{-3})	0.35	K (mg L^{-1})	0.60
Permanent wilting point (cm^3 cm^{-3})	0.21	$CaCO_3$ (mg L^{-1})	326.90
Bulk density (g cm^3)	1.26	pH	6.82
EC (dS m^{-1})	0.50		
P (mg kg^{-1})	20.00		

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

EC		Cl	Na	Ca	HCO_3
(dS m^{-1})	pH	----------- (mg L^{-1})	----------	----------	----------
0.6	7.95	60.3	19.2	128.0	388.1
1.5	8.01	414.8	96.6	224.0	306.4
2.5	7.70	620.2	110.5	388.4	306.4
3.0	7.91	719.6	136.6	497.0	306.4
3.5	7.30	1505.9	175.7	670.4	294.3
4.5	7.52	1772.5	226.9	882.0	245.1
6.0	7.25	2230.3	359.6	1523.0	265.6

The salinity levels of the irrigation water were 0.6 (tap water), 1.5, 3.0, 4.5 and 6.0 dS m^{-1} in year 2005 and 0.6 (tap water), 1.5, 2.5, 3.5 and 4.5 dS m^{-1} in year 2006 obtained by adding NaCl and $CaCl_2$ to the tap water with equal equivalent proportion. The chemical analysis of saline irrigation water is shown in Table 2. The experimental layout was a 3×5 factorial arrangement with four replications. The maximum and minimum air temperatures were 37±7 and 15±5°C, respectively.

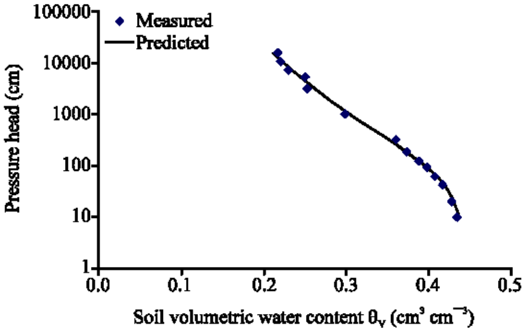

Fig. 1: Soil moisture curve

Undisturbed samples of soils were used to determine the soil water retention curve by hanging water column and pressure plate apparatus. The soil water retention curve is shown in Fig. 1. Soil water content before each irrigation in pots was measured by weighing the pots. Seven times during the growing season drainage water was collected. Electrical conductivity, chloride, Ca+Mg and Na were determined in the drainage water during the growing season. Osmotic potential of the drainage water as soil solution was estimated by the following equation (Richards, 1954):

$$h_o = -360\times EC_{ss}$$

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 was converted to soil water matric potential by using the soil water retention curve (Fig. 1). Similar pots were 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.

At harvest, the plants were cut at the soil surface and plant tops were dried in an oven at 65°C for 48-72 h. Grains were separated from straw and weighed. The grain weight was corrected to 14% moisture content. Soil samples were collected from pots for chemical analysis. Electrical conductivity, chloride, Ca+Mg and Na were determined in soil saturation extracts.

RESULTS AND DISCUSSION

Table 3: Soil matric and osmotic potentials at different points in the range of their variations

Potential different point	Potential value (cm)
Matric h_3	96
h_{50}	873
h_{max}	11334
Osmotic h_o*	1747
h_{o50}	3071
h_{omax}	43941

Table 4: Mean water uptake function, $\alpha(h,h_0)$, with different Eq. 3, 4, 8-10

Treatment	Eq. 10	Eq. 3	Eq. 4	Eq. 9	Eq. 8	Measured
S_0W_0	0.998	0.653	0.864	0.998	0.769	1.000
S_0W_1	0.794	0.699	0.696	0.999	0.541	0.794
S_0W_2	0.740	0.574	0.616	0.996	0.476	0.730
S_1W_0	0.681	0.130	0.599	0.676	0.585	0.700
S_1W_1	0.883	0.303	0.601	0.989	0.678	0.851
S_1W_2	0.845	0.183	0.483	0.908	0.565	0.773
S_2W_0	0.465	0.044	0.949	0.457	0.448	0.483
S_2W_1	0.837	0.114	0.474	0.853	0.586	0.817
S_2W_2	0.698	0.062	0.369	0.724	0.451	0.707
S_3W_0	0.178	0.017	0.390	0.174	0.315	0.193
S_3W_1	0.559	0.027	0.326	0.576	0.369	0.563
S_3W_2	0.561	0.030	0.305	0.592	0.356	0.579
S_4W_0	0.111	0.010	0.354	0.108	0.270	0.113
S_4W_1	0.382	0.014	0.269	0.423	0.273	0.402
S_4W_2	0.374	0.016	0.303	0.427	0.310	0.403

Root-water uptake coefficient: The ratio of actual transpiration to potential transpiration is defined as root-water uptake coefficient (α), however, in this study, evapotranspiration (ET) was assumed equivalent to transpiration. Therefore, α was taken as the ratio of actual ET to potential ET. Furthermore, Eq. 3, 4, 8-10 were used to estimate the values of α. In these estimations the corresponding values of soil matric and osmotic potentials were determined by Sepaskhah and Yousofi-Falakdehi (2009) and are presented in Table 3. The measured and estimated mean values of root-water uptake coefficients by different methods are shown in Table 4.

The estimated values of α by Homaee and Feddes (1999) Eq. 10 are closed to those of measured values. The additive equation for root-water uptake coefficient proposed by Van Genochten (1987) Eq. 3 predicted the values of α very lower than the measured values. Therefore, it is indicated that the additive equation by Van Genochten (1987) is not appropriate for estimation of α for rice.

The estimated values of α by Dirksen *et al.* (1993) Eq. 8 are closer to the measured values (Table 4) but it is not as good as Eq. 10. The estimated values of α by Maas and Hoffman (1977) Eq. 9 are the closest to those predicted by Homaee and Feddes (1999) Eq. 10. These results are in support of those obtained for saffron as reported by Sepaskhah and Yarami (2010). The relationships between the predicted and measured values of α are determined by linear regression. The statistical results are shown in Table 5. The slope of linear relationship between the estimated $\alpha(h,h_o)$ by additive function (Van Genochten, 1987) and the measured values was statistically close to 1.0 but its intercept was statistically different from zero. The slopes of linear relationships between the estimated $\alpha(h, h_o)$ by multiplicative functions (Maas and Hoffman, 1977;

Table 5: The results of F-test analysis predicted water uptake function with calculated values

						Probability level (5%)	
Eq. No.	Linear equation	R^2	n	SE	P	Slope	Intercept
Eq. 3	α_p=0.9495 α_m-0.43	0.51	60	0.172	3.50E-06	NS	S
Eq. 4	α_p =0.768 α_m -0.026	0.68	60	0.096	5.90E-16	S	NS
Eq. 8	α_p =0.797 α_m -0.055	0.88	60	0.055	0.046	S	NS
Eq. 9	α_p =1.430 α_m -0.27	0.78	60	0.139	1.60E-04	S	NS
Eq. 10	α_p =1.023 α_m -0.023	0.99	60	0.039	1.00E-04	NS	NS

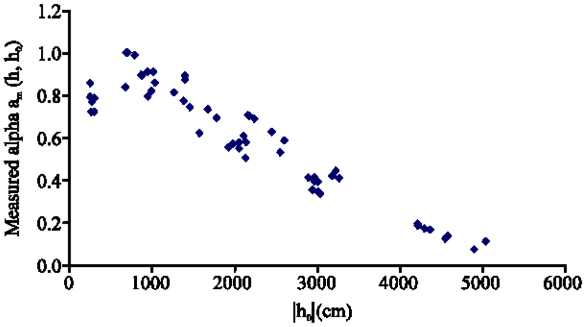

Fig. 2: Variation of water uptake function with osmotic potential in all of treatments

Van Genochten, 1987; Dirksen *et al*., 1993) and the measured values were statistically different from 1.0 but their intercepts were statistically close to zero. Therefore, the additive and multiplicative functions are not appropriate for estimation of $\alpha(h, h_0)$. Finally, the slope and intercept of the linear relationship between estimated $\alpha(h, h_0)$ by the combination function (Homaee and Feddes, 1999) and the measured values were statistically close to 1.0 and zero, respectively. Therefore, the combination function of Homaee and Feddes (1999) is appropriate for estimation of $\alpha(h, h_0)$.

Variation of root-water uptake coefficient with osmotic potential: As soil osmotic potential ($-h_0$) is decreased, total soil water potential is reduced and soil water is less available to plant. Figure 2 shows variation of root-water uptake coefficient with osmotic potential for all treatments. Root-water uptake coefficients increased by decrease in the soil osmotic potential from salinity levels of S_0 to S_1 and reach a maximum at salinity level of S_1 and then reduced with further decrease in soil osmotic potential at higher salinity levels. This is in accordance to the finding of Sepaskhah and Yousofi- Falakdehi (2009). They reported that rice dry matter in S_1 treatment was more than S_0. Furthermore, Sepaskhah *et al*. (2006) showed that root yield of sugar beet increased under soil saturation extract salinity levels up to 1.0 dS m^{-1} then decreased with increase in salinity levels.

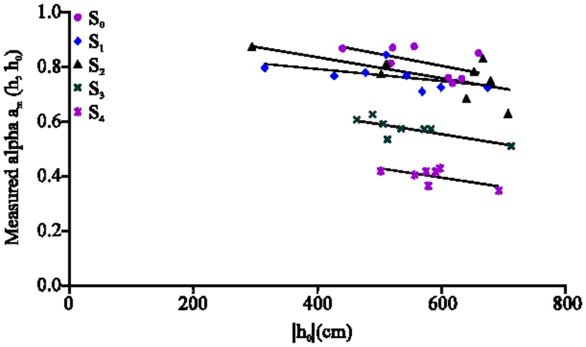

Fig. 3: Variation of water uptake function with matric potential in all of treatments

Variation of root-water uptake coefficient with matric potential: The values of α as a function of soil matric potential for different soil water osmotic heads (salinity levels) are shown in Fig. 3. The values of α were decreased by reduction in soil matric potential and soil osmotic potential at salinity levels greater than S_2. The values of α at salinity level of S_1 were higher than those at salinity level of S_0 for all soil matric potentials. This is in accordance with those discussed in the earlier.

Yield prediction with root-water uptake coefficient: For prediction of rice grain yield, reported value of K_y by Sepaskhah and Yousofi-Falakdehi (2009) (1.14) was used in Eq. 15 and 16. The relationships between the predicted rice grain yield per pot by Eq. 16 and 15 and the measured values are shown in Fig. 4 and 5, respectively. The calculated values of α by Homaee and Feddes (1999) were used in Eq. 15. Poor estimation of rice grain yield was obtained in FAO method Eq. 16 with coefficient of determination (R^2) of 0.44 and 0.63 and slopes of 0.73 and 0.67 for 2005 and 2006, respectively. However, good estimation of rice grain yield was resulted from Homaee and Feddes (1999) method Eq. 15 with R^2 of 0.93 and 0.94 and slopes of 0.89 and 0.83 for 2005 and 2006, respectively. These results are in accordance to the findings of Sepaskhah and Yarami (2010) for saffron. In FAO method, the calculated values of K_s from Eq. 13 were negative for continuous irrigation with high

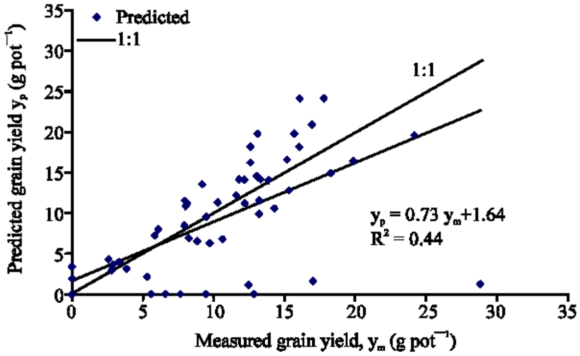

Fig. 4: Comparison of predicted yield from Eq. 14 with 1:1 line (2005)

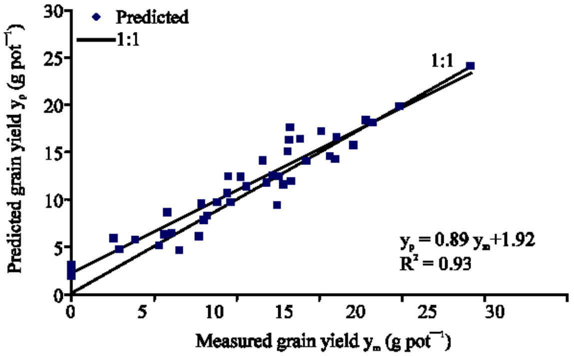

Fig. 5: Comparison of predicted yield from Eq. 15 with 1:1 line (2005)

salinity levels. Therefore, poor estimation of the FAO method was obtained.

CONCLUSIONS

Results indicate that the additive function for root-water uptake presented by Van Genochten (1987) Eq. 3 is not suitable for prediction of root-water uptake coefficient to show the interaction effect of salinity and deficit irrigation on yield prediction. Further, the Dirksen *et al.* (1993) Eq. 8 and multiplicative function proposed by Van Genochten (1987) resulted better estimation of roo-water uptake coefficient than that of additive function of Van Genochten (1987), but still they are not suitable. The Mass and Hoffman (1977) Eq. 9 resulted better estimation of α than those of other additive and multiplicative functions, however, it was not better than those obtained by Homaee and Feddes (1999) equation. This method often predicted α value higher than the measured values. Finally, it is concluded that the best equation for prediction of root-water uptake coefficient is the Homaee and Feddes (1999) Eq. 10. Also, rice yield was predicted by using this equation and FAO method along with production function presented by Stewart *et al.* (1977). Results indicated that the FAO method did not predict the yield properly especially in continuous flooding and salinity level of more than threshold values, but the Homaee and Feddes (1999) method predicted the grain yield properly with a minimum error.

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