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Field evaluation of water uptake reduction functions under conjunctive salinity and water stress conditions (case study: wheat, ghods variety)

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ABSTRACT

Plants often experience both drought and salinity stress in arid environment. Various mathematical water uptake models exist for plants response to combined drought and salinity stress. The reduction functions are classified as additive, multiplicative and conceptual models. In this study six different macroscopic reduction functions, namely; Van Genuchten (additive and multiplicative), Dirksen et al., Van Dam et al, Skaggs et al and Homaee were evaluated. The experiment was carried out on Ghods variety of wheat crop in a factorial split plot design with 3 replicates in the Research Field of university Birjand. The treatments consisted of four levels of irrigation (50, 75, 100 and 120% of crop water requirement), and three water qualities (1.4, 4.5, 9.6 dS/m). The results of this study indicated that the additive model estimates relative yield less than actual amount. In other word, the effect of combined stresses on wheat yield was less compared to sum of the separate effects due to salinity and water stress. The effect of drought stress on reduction of yield was more than salinity stress. The results also revealed that reduction function of Skaggs et al and Homaee were better fitness to measured data than the other functions.

Introduction

Most salt stress and water stress studies have been carried out separately and many data are available for only one of these stresses. It is well known that water uptake is reduced due to salinity, but it is not yet clear how plants react when low soil water pressure head h occurs together with low osmotic head h_0. In the earliest studies (Wadleigh and Ayers, 1945; Wadleigh et al., 1946; US Salinity Laboratory Staff, 1954), the investigators proposed that joint effect of salinity and water stress on water consumption may be relative to the total soil water osmotic and pressure heads. The concept of total was later specified as the sum of these two components, from which the additivity concept was born. The model proposed by Nimah and Hanks (1973) belongs to this approach. Some researchers clearly showed that one unit π does not influence the water consumption the same as one unit of *h* (Homaee, 1999). The proponents of additivity suggested that some empirical proportionality coefficients should be included in the linear additivity of π and *h* (Meiri, 1984; Shalhevet, 1993). Such empirical coefficients are considered to be plant, soil, and climate specific, but never been quantified in the literature. Recent reviews of the conceptual models of root water uptake under water and salinity stress are given by Homaee (1999) and Homaee and Feddes (1999). The so-called multiplicativity concept is based upon the product of the separate reduction terms for soil water osmotic heads and pressure heads (Van Genuchten, 1987; Dirksen et al., 1993; Homaee and Feddes, 2001). This concept was originally proposed by Van Genuchten (1987) and has been used extensively in many numerical simulation models dealing with root water uptake.

The objective of this paper is to investigate the joint influence of different levels of h and π on root water uptake patterns, and to investigate which concept fits experimental data best, or what adjustments need to be made.

Theory

The governing flow equations and the reduction functions under separate salinity and water stress are given in preceding papers (Homaee et al., 2002a, b). The available macroscopic reduction functions for the combined stresses can be divided into three categories: additive (Van Genuchten, 1987), multiplicative (Van Genuchten and Hoffman, 1984; Van Genuchten, 1987; Dirksen et al., 1993; Van Dam et al., 1997; Homaee, 1999) and the conceptual combined method (Homaee, 1999). The additive reduction function (Van Genuchten, 1987) reads:

$$\alpha(h,\pi)=\frac{1}{1+\left[\dfrac{h(z,t)+\pi(z,t)}{h_{50}}\right]^{p}} \qquad (1)$$

The multiplicative reduction function proposed by Van Genuchten (1987) reads:

$$\alpha(h,\pi)=\frac{1}{1+(\dfrac{h}{h_{50}})^{p_1}}\times\frac{1}{1+(\dfrac{\pi}{\pi_{50}})^{p_2}} \qquad (2)$$

Dirksen and Augustijn (1988) and Dirksen et al. (1993) multiplied identical reduction terms for water stress and salinity stress, each with their own values for the threshold value *h**, π * and value $h_{0.5}$ and $\pi_{0.5}{}^{*}$:

$$\alpha(h,\pi)=\frac{1}{1+\left[(h-h^*)\big/(h^*-h_{50})\right]^{p_1}}\times\frac{1}{1+\left[(\pi-\pi^*)\big/(\pi^*-\pi_{50})\right]^{p_2}} \qquad (3)$$

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Van Dam et al. (1997) simply multiplied the water stress reduction functions of Feddes et al. (1978) and Maas and Hoffman (1977) as:

$$\alpha(h,\pi)=\frac{h-h_4}{h_3-h_4}\times\left[1-\frac{b}{360}(\pi^*-\pi)\right] \tag{4}$$

Homaee (1999) proposed for the combined stresses:

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

All the parameters used in the above equations are defined in the preceding papers. After presenting detailed experimental data and encountering the limitations of additive and multiplicative reduction functions Homaee (1999) combined the reduction functions of Feddes et al. (1978) with that of Maas and Hoffman (1977) and proposed:

$$\alpha(h,\pi)=\frac{h-(h_4-\pi)}{h_3-(h_4-\pi)}\times\left[1-\frac{b}{360}(\pi^*-\pi)\right] \tag{5}$$

This equation is valid for $\pi < \pi^*$ and (h4 - π) < h < h3, respectively. Other general validities are the same as the original models. This model that differs conceptually from additive and multiplicative approaches is based upon the assumption that the reduction function of Maas and Hoffman (Fig. la) can be directly employed in the nostress part (Section 2, Fig. lb) of Feddes et al.'s model. Fig. l shows such combination when the reduction due to salinity stress alone is 30% (a = 0.7). Further assumption is that each ds/m salinity beyond the threshold value (EC*) shifts the wilting point 360 cm to the left. This is consistent with the observation that plants wilt at higher soil water pressure head in the presence of salinity than without salinity. The magnitude of 360 is only a preliminary guess based on the well-known empirical relation in USDA Handbook 60 to transfer soil salinity to osmotic head (US Salinity Laboratory Staff, 1954) and was used until further evidence provides a more precise quantity. The effect of each level of joint water and salinity stress can then be obtained as illustrated in Fig. Id. The applicability of this model for some detailed experimental data is extensively discussed by Homaee et al (2002c).

Skaggs (2006) combined the reduction functions of Van Genuchten (1978) for water stress with that of Maas and Hoffman (1977) for salinity stress and proposed:

$$\alpha(h,\pi)=\frac{1}{1+(\frac{h}{h_{50}})^{p_1}}\times\left[1-\frac{b}{360}(\pi^*-\pi)\right] \tag{6}$$

Materials and methods

In this part of the study, different levels of salinity (S1, S2 and S3) and water stresses (W1,W2, W3 and W4) have been applied to Ghods variety of wheat crop simultaneously, using an individual reference treatment *R* for each water stress level. The field study was conducted during 2005-2006 growing season in the Research Field of university Birjand in Iran. The field is in the eastern part of Iran (latitude 32◦53_N, longitude 13◦55_E and altitude 1480m above sea level) within a main agricultural region with relatively low precipitation and no groundwater impact on the rooting zone. The mean annual precipitation (1961–1990) is 173mm and the mean annual temperature 16.6 ◦C. Water and salinity stresses were applied to wheat crop after healthy plants had developed. The target water applications were 50, 75, 100 and 125% of the reference for W1, W2, W3 and W4, respectively. The irrigation water salinities were 1.5, 4.5 and 9.6 dS/m for S1, S2 and S3, respectively. The experiment was carried out on in a factorial split plot design with 3 replicates. The treatments consisted of four levels of irrigation (50, 75, 100 and 125% of crop water requirement), and three water qualities (1.4, 4.5, 9.6 ds/m). The array of irrigation system and experimental plots were mapped in Fig1. All possible combinations of the mentioned water and salinity stresses with their own references were applied variations of soil water content, soil water pressure head, and osmotic head distributions in the root zone were obtained by varying the quantity of applied water, irrigation intervals, and irrigation water salinities.

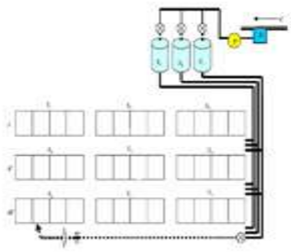

Fig1. Schematic map of experiment

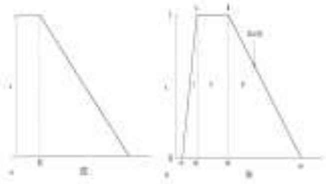

Fig. 2. Schematic illustration of reduction functions of: (a) Maas and Hoffman; (b) Feddes et al.; (c) direct application of a(h_0) = 0.7 into no-stress part of Feddes et al.; and (d) combined reductions due to h and π

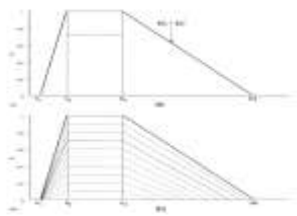

Fig. 2. (Continued)

Results and discussion

Among the combined reduction functions, Eq.(1) represents an additive form of water and salinity stress. Because values for the proportionality coefficients a1 and a2 in Eq. (1) are not available, Eq. (1) is simplified to a simple linear additivity of h and or a1=a2 =1. Fig. 2 presents the fit of the additive (Eq (1)), multiplicative (Esq. (2)-(4)), and newly proposed combination (Esq. (5), (6)) reduction functions with the experimental relationship of α = T/Tp versus mean h, for mean ECSS of 1.4 ds/m. As can be seen, Eq. (6) gives the best fit, while the worst agreement belongs to Eq (1).

Eqs. (4) and (5) both represent a combination of the Feddes et al. (1978) and Maas and Hoffman (1977) models. Fig. 3,4 and 5 compare the six models against experimental data for a mean ECSS over the root zone of 4.5 and 9.6 ds/m. The simple product of the separate osmotic and pressure head components in Eq. (4) keeps h4 (wilting point) constant in the saline condition. In contrast, Eq. (5) follows the experimental trend that with increasing salinity wilting occurs at higher soil water pressure heads. As the salinity increases, the disagreement between the two equations becomes greater. These results indicate that neither the multiplicative nor the additive reduction functions fit the experimental data satisfactorily.

The best fits were obtained with Eq. (5) and (6), which combine the linear salinity reduction function of Maas and Hoffman (1977) with the pressure head reduction function of Feddes et al. (1978) and Van Genuchten (1978), respectively. The results of this study indicated that the additive Eq. (1) generally gave the worst agreement with the experimental data. This model estimates relative yield less than actual amount. In other word, the effect of combined stresses on wheat yield was less compared to sum of the separate effects due to salinity and water stress. From a practical point of view, Eq. (6) appears to be accurate enough (Fig. 2). The parameter values for the Maas and Hoffman equation are available for many plants, while those of the non-linear functions are difficult to obtain.

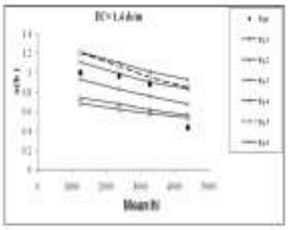

Fig. 2. Comparison between additive (Eq. (1)), multiplicative (Eqs. (2)-(4)) Eq. (5) and Eq. (6) with the experimental relationship of α = *Ta/Tv* vs. mean pressure head for mean EC_{SS} of 1.4 dS/m.

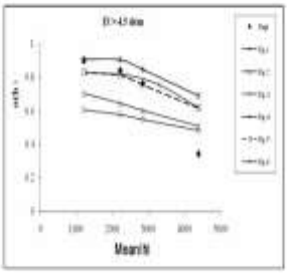

Fig. 3. Comparison between additive (Eq. (1)), multiplicative (Eqs. (2)-(4)) Eq. (5) and Eq. (6) with the experimental relationship of α = *Ta/Tv* vs. mean pressure head for mean EC_{SS} of 4.5 dS/m.

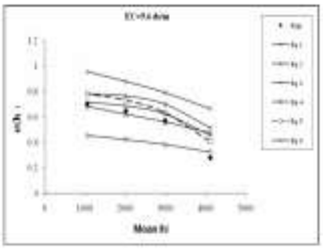

Fig. 4. Comparison between additive (Eq. (1)), multiplicative (Eqs. (2)-(4)) Eq. (5) and Eq. (6) with the experimental relationship of α = *Ta/Tv* vs. mean pressure head for mean EC_{SS} of 9.6 dS/m.

In the simulations, the input parameter values for the different reduction terms have been obtained from the previously calibrated treatments of separate salinity and water stress. Thus, no calibration was made for the 12 joint water and salinity stress treatments. The parameter values used in the simulations are given in Table 1.

The final argument on the simulation performance of the various reduction functions can be based upon the comparison of the measured and simulated actual relative yield. Table 2 gives this comparison for S_1W_1, S_1W_2, S_1W_3, S_1W_4, S_2W_1, S_2W_2, S_2W_3, S_2W_4, S_3W_1, S_3W_2 S_3W_3 and S_3W_4 treatments. Eqs. (5) and (6) provide the closest agreement in most treatments. At the lower soil solution salinities, Eq.(4) performs very closely to Eq. (5). Both equations combine the Feddes et al. (1978) and Maas and Hoffman (1977) functions. The main difference between Eqs.(4) and (5) is the slope of the reduction line due to salinity. Eq. (4) keeps h_4 constant at different salinities, and the slope of the line changes with the height of the horizontal segment for no-water-stress. In Eq. (5), h_4 decreases with increasing salinity, and thus, the slope of the line changes accordingly. Since at low salinities the h_4 values in both equations are very close to each other, both equations provide almost similar results. As the soil solution salinity increases the difference between the equations becomes larger and Eq. (4) fails to follow the reality.

Quantitative comparison of experimental and simulated actual relative yield

In the preceding two papers (Homaee et al., 2002 a, b), the residual errors between the simulated and experimental results of the separate stresses have been analyzed to evaluate the performance of the various reduction functions. The same statistics are employed here, namely maximum error (ME), root mean square error (RMSE), coefficient variation (CV), coefficient of determination (R^2), modeling efficiency (EF), and coefficient of residual mass (CRM). The mathematical expressions of these statistics are given in Homaee et al. (2002a), and the values calculated for the actual relative yield simulated with Eqs. (l)-(6) are given in table 3. The worst simulation results are obtained with the simple additivity of Eq. (1), while Eq. (6) performs the best results. Eq (6) to overestimate or underestimate (CRM) is less than that of other equations. Tables 3 indicates that the root mean square errors with Eq. (6) is minimum between all models, which indicates that for these twelve models all other equations provide over and/or underestimates of the cumulative actual yield.

Also, the simulated relative yield with Eq.(6) provides less scatter with the experimental function of Van Genuchten (1978). The simulated relative yield was compared with the experimental data.

The relation between relative yield and mean soil water pressure head $|h|$ was more or less linear for all mean soil solution salinities EC_{SS} except for the lower level of EC_{SS} = 1.5 ds/m. As the mean soil solution salinity increased, the trend became more linear. The linear trend is in agreement with the reported experimental data for the salinity stress treatments but not with the non-linear trend obtained for the water stress treatments. The experimental results clearly support Eq (6), particularly for the higher soil solution salinities. While Eq. (6) contains a linear salinity reduction function, it is still flexible to be used with any non-linear salinity reduction term. However, these expressions give no significant improvement in the comparison with the presented experimental data. Eq. (6) has the advantage of simplicity and requires fewer input values.

The comparison between the experimental and simulated relative yield indicates that Eq. (6) provides the best results. Among the multiplicative functions, Eqs (2) and (3) provide the better results. Since Eq. (3) requires parameter values of h^*, π^* that are difficult to obtain, it is more convenient to use Eq. (2). The simple additivity of Eq. (1) always provides the worst agreement with the experimental data. With Eq. (6), the simulation model provides reasonably good agreement with the experimental relative yield. Some discrepancies were observed, but the trend of the simulated data was reasonable. The discrepancy between the simulated and experimental relative yield is partly due to the way water uptake is calculated.

The potential transpiration is distributed equally over each soil increment and the water uptake is calculated according to its own reduction function and root activity, independent of the uptake in other increments. Integration of these uptake increments over the root zone yields the total uptake. In reality, the plant can take up the required water from any depth if there are active roots. Root systems are reasonably flexible to adjust to water uptake at other depths to reach their evaporative demand. Water flow in the soil in compensation of water depletion due to root water uptake at other depths also seems to be an important phenomenon, which has to be taken into account in a proper way. More research is needed to verify and quantify this. All observations clearly support the newly proposed Eq. (6). The magnitude of the soil water pressure head at which wilting occurs at different salinities, however, needs more investigations data than the other equations. In conclusion, for most treatments Eq. (6) yields the best agreement with the measured relative yield.

Conclusions

Six different soil water pressure head dependent reduction functions were used in the macroscopic sink term. The results of this research shows that the relation between relative yield and mean soil water pressure head $|h|$ was more or less linear for all mean soil solution salinities EC_{SS} except for the lower level of EC_{SS} = 1.5 ds/m.. As the mean soil solution salinity increased, the trend became more linear. The linear trend is in agreement with the reported experimental data for the salinity stress treatments but not with the non-linear trend obtained for the water stress treatments. The experimental results clearly support Eq. (6), particularly for the higher soil solution salinities. While Eq. (6) contains a linear salinity reduction function, it is still flexible to be used with any non-linear salinity reduction term. However, these expressions give no significant improvement in the comparison with the presented experimental data. Eq. (6) has the advantage of simplicity and requires fewer input values.

The comparison between the experimental and simulated relative yield indicates that Eq. (6) provides the best results. The additive Eq. (1) generally gave the worst agreement with the experimental data. This model estimates relative yield less than actual amount. In other word, the effect of combined stresses on wheat yield was less compared to sum of the separate effects due to salinity and water stress. Among the multiplicative functions, Eqs. (3) and (4) provide the better results. Since Eq. (3) requires parameter values of $h_{50}, \pi_{0.5}$, P_1 and P_2 that are difficult to obtain, it is more convenient to use Eq. (5). The simple additivity of Eq. (1) always provided the worst agreement with the experimental data. With Eq.(5) and (6), the simulation model provides reasonably good agreement with the experimental data.

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Table 1) Parameter values used in simulations with various reduction functions

P_2	P_1	α	π_{50}	h_{50}	h_4	π^*	$h_3 = h^*$
1.73	1.13	0.07	-11000	-8500	-15000	-4200	-1000

Table 2) Experimental and simulated relative yield for S_1I_1 S4WU SiW2 and S4W2 treatments, using different reduction functions.

Predicted relative yield by reduction functions						Experimental relative yield	π(cm)	h(cm)	Treatment
Eq_6	Eq_5	Eq_4	Eq_3	Eq_2	Eq_1				
0.83	0.85	0.93	0.68	0.56	0.54	0.434	-3035	-4396	S_1W_1
0.9	0.96	1.01	0.76	0.62	0.58	0.879	-3125	-3284	S_1W_2
0.99	1.07	1.1	0.83	0.68	0.62	0.964	-3051	-2385	S_1W_3
1.11	1.21	1.21	0.93	0.74	0.68	1.00	-2999	-1254	S_1W_4
0.62	0.58	0.69	0.7	0.51	0.48	0.344	-4667	-4385	S_2W_1
0.76	0.79	0.84	0.83	0.6	0.55	0.736	-4332	-2841	S_2W_2
0.81	0.86	0.9	0.88	0.64	0.57	0.84	-4254	-2215	S_2W_3
0.83	0.9	0.9	0.97	0.74	0.61	0.898	-4607	-1206	S_2W_4
0.46	0.41	0.51	0.67	0.48	0.45	0.28	-5947	-4112	S_3W_1
0.62	0.63	0.7	0.79	0.56	0.51	0.57	-5143	-2995	S_3W_2
0.69	0.73	0.77	0.88	0.62	0.55	0.647	-5098	-2012	S_3W_3
0.72	0.78	0.78	0.96	0.68	0.58	0.702	-5296	-1053	S_3W_4

Table 3) Statistics used to compare the different reduction functions for total treatment against the experimental actual relative yield

Eq_6	Eq_5	Eq_4	Eq_3	Eq_2	Eq_1	functions reduction
0.399(1)	0.41(2)	0.49 (3)	0.273 (5)	0.28(4)	0.34(3)	ME
0.102(1)	0.12(1)	0.17 (3)	0.207(5)	0.157(4)	0.201(5)	AE
0.155(1)	0.163(2)	0.214 (3)	0.213(5)	0.182(4)	0.22(6)	RMSE
0.88(1)	0.83(2)	0.83(2)	0.51(3)	0.22(4)	0.69 (5)	R^2
22.35(1)	23.52 (2)	30.84 (4)	30.97(5)	26.22(3)	32.02(6)	C.V
0.554(1)	0.507(2)	0.152(4)	0.145 (5)	0.38(3)	0.39(6)	EF
-0.121(1)	-0.154(3)	-0.245(6)	-0.2 (4)	0.109(2)	0.19(6)	CRM
1.57	2	5	4.83	3.83	5.83	Average of rank
(1)	(2)	(5)	(4)	(3)	(6)	Final rank