

Root water uptake under heterogeneously distributed soil salinity

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Abstract

Quantitative understanding of how plants integrate water under variable soil salinity is crucial for soil-water budget simulation models dealing with solutes. The objective of this study was to investigate how plants integrate under heterogeneously distributed soil salinity over its rooting depth. Consequently, a detailed experiment with alfalfa (*Medicago Sativa* L.) was conducted in packed micro-lysimeters with loamy sand soil. Different soil salinities were created by changing the quantity and quality of saline water applied to the soil columns. No water deficit was allowed for the entire growth period. The collected data were sorted in three mean salinity groups and the water extraction rate for each soil compartment was calculated with Richards' equation. The results under different levels of soil salinities indicated that the uptake rate preliminary reacts to soil salinity, whereas at given water content and salinity the "evaporative demand" and "root activity" become more important to control the uptake pattern. Under heterogeneously distributed osmotic head, most of the water was taken from the less saline part of the root zone, but the uptake at other parts with higher salinities was never stopped. The results also indicated that root activity is inconstant during the stress period. By salinity increase, the activity of that part of the root system was also increased. Thus, the reduced uptake in one compartment due to high salinity is not only compensated from other parts with lower salinities, but also from the same increment by increasing root activity.

Introduction - Theory

Theoretical concepts of how plants integrate soil salinity have not been fully developed and verified. When salinity is distributed heterogeneously over the root zone, it is frequently assumed that the plant responds to the average soil salinity and some collected data support this idea (Prunty, et al., 1991). Concerning this heterogeneity, there are three contradictory ideas in the literature. The first suggests that the water uptake can better be related to the salinity of the upper part of the root zone than that of the deeper part (Smith, 1994). The second states that the relative uptake is strongly affected by the more saline part in the root zone which is mainly located at the deeper part of the soil profile (Francois, 1981). The third, proposed that the plant response can be described better by some weighted mean salinity (Raats, 1974). One more approach that can be regarded as an averaging concept is the algorithm used in numerical simulation models. Usually these models (e.g. Simunek et al., 1998; Van Dam et al., 1997; Dirksen et al., 1993) distribute the potential transpiration over the root zone according to the specified root activity distribution. The actual transpiration is considered to be equal to the potential transpiration until the threshold salinity is reached. The actual transpiration is then calculated for every node according to the specified reduction function. The integration of the calculated transpiration over all the nodes gives the actual transpiration for the entire root zone. When the soil salinity differs with depth, the model assumes that water can be taken up independently at every depth according to the specified reduction function and the relative root activity. The water contents and salinities are then calculated according to the water depletion at each node.

One-dimensional water flow in unsaturated soil is described with *Richards'* equation (*Richards*, 1931). Including the root extraction term S it reads:

$$\frac{\partial \theta}{\partial t} = C(h) \frac{\partial h}{\partial t} = \frac{\partial}{\partial z} \left(K(h) \frac{\partial h}{\partial z} + K(h) \right) - S(h) \quad [1]$$

where θ is volumetric water content (L^3L^{-3}), t is time (T), h is soil water pressure head (L), $C = d\theta/dh$ is the differential soil water capacity (L^{-1}), z is gravitational head, as well as the vertical coordinate (L) taken positive upward, q is the soil water flux density (LT^{-1}), K is soil hydraulic conductivity (LT^{-1}), and S is the sink term ($L^3L^{-3}T^{-1}$).

The macroscopic sink term as function of soil salinity expressed as osmotic head h_o (L) can be written as:

$$S = \alpha(h_o) T_p \delta \quad [2]$$

where δ (L^{-1}) is the relative root activity defined such that the integer of δ over the root zone equals unity, and $\alpha(h_o)$ is the osmotic head reduction function. The proposed S-shaped $\alpha(h_o)$ function by Dirksen et al. (1993) reads:

$$\alpha(h_o) = \frac{1}{\left[1 + \left(\frac{h_o^* - h_o}{h_o^* - h_{o50}} \right)^p \right]} \quad [3]$$

where h_o^* and h_{o50} are the osmotic head threshold value and the osmotic head at which the uptake rate reduced to 50 percent, respectively.

Materials and methods

Alfalfa (*Medicago Sativa* L.) was seeded in packed cylindrical soil columns with a height of 65 cm and a diameter of 21 cm. The measurements started after healthy plants had developed in the greenhouse. Assuming no significant water uptake during the dark period, all irrigation waters were applied to the columns by flood irrigation immediately before turning off the lights. Water salinities were varied around the salinity threshold value of alfalfa, i.e. at 1.5, 2.0, 3.0, 4.0, and 5.0 dS/m, denoted as S_1 , S_2 , S_3 , S_4 , and S_5 treatments, respectively. A reference treatment R without any salt or water stress was also established to compare the stressed treatments data and to obtain the evaporative demands under which the data were collected. To prevent evaporation from the soil surface, the top of each column was covered by inert granules. Soil solution salinities EC_{ss} were measured in-situ with salinity sensors and a salinity bridge. All sensors were installed horizontally into the soil columns in one row at depth intervals of 5 cm in the top 30 cm and at 10 cm intervals below that. The same order of depth intervals was followed for the TDR sensors. Soil water content θ was measured with fully automated TDR equipment, using a cable tester, a multiplexer and control system. Soil water pressure heads h were obtained by converting θ to h based on the soil water retention characteristics. The hydraulic parameter values were derived, using the RETC program (Van Genuchten et al., 1991). The hydraulic functions of the soil used in this study are given by Homae (1999). Actual T_a and potential T_p transpirations were obtained by weighing the columns. Leaf water potentials LWP were measured with a pressure chamber.

Results and discussions

Table 1 represents some data obtained from relatively high saline columns, having some similar averaged characteristics. The data were collected under different evaporative demand conditions, specified by potential transpiration T_p . The calculated uptake rates S in this table is given for 10-hour time intervals. The water contents were high enough to prevent any water deficit. Since the plants in each container were treated uniformly before creating any salt stress, the root density was the same in all the columns.

Table 1. Some experimentally obtained parameters with similar averaged characteristics.

Soil Column	Depth cm	EC_{ss} dS/m	θ cm ³ /cm ³	S 10 ⁻³ cm ³ /cm ³ h	T_a mm/d	T_p mm/d	T_a/T_p	LWP_R/LWP_{Si}
I	5	6.3	0.27	1.44				
	10	8.3	0.20	0.70				
	15	13.7	0.26	0.47				
	20	20.0	0.25	0.15				
	25	17.5	0.20	0.35	0.87	1.73	0.50	0.60
	35	10.7	0.33	0.64				
	45	4.8	0.36	1.45				
	55	1.8	0.37	4.47				
	Average	9.1	0.30	1.47				
J	5	5.9	0.24	1.85				
	10	7.5	0.20	1.74				
	15	11.2	0.24	1.10				
	20	16.2	0.24	0.76				
	25	16.5	0.19	0.17	1.41	2.71	0.52	0.63
	35	12.5	0.31	1.02				
	45	7.0	0.35	1.96				
	55	2.1	0.37	4.91				
	Average	9.1	0.29	1.95				
K	5	6.7	0.24	1.09				
	10	9.0	0.19	0.71				
	15	11.5	0.25	0.63				
	20	16.2	0.35	0.13				
	25	16.2	0.36	0.36	1.95	4.06	0.48	0.56
	35	12.5	0.26	0.45				
	45	7.0	0.37	1.04				
	55	2.1	0.38	2.36				
	Average	9.3	0.31	0.96				

Besides having such a uniform distributions, it appeared that the root activity has a dynamic change during the stress period. Figure 1a shows such a dynamic for a column at 2h time intervals.

While the mean EC_{ss} in the columns was 5 times larger than alfalfa's threshold value ($EC^* = 2$ dS/m), soil salinities at some points were even more than 10 times of this value. Under such conditions the interesting question is whether the root water uptake will cease at extremely high soil salinity compartments. Also, interesting is to find out which concept of water integration can hold under this circumstances.

While the water uptake rate as function of soil solution salinity in Table 1 shows a diminishing trend at most of the compartments, it is obvious that S does not decrease uniquely by 1 dS/m increase in EC_{ss} . Such a trendless behavior is given in Fig. 1b for our experimental data at constant water contents.

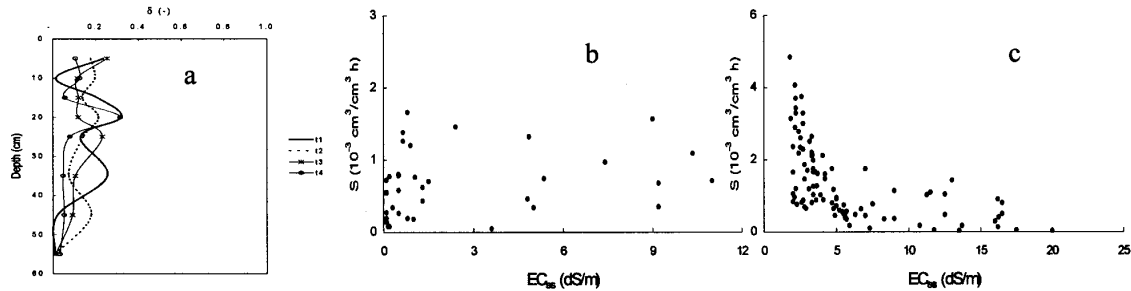


Figure 1. Relative root activity distribution (a); the sink term versus EC_{ss} at constant θ (b) and at each compartment (c).

In column J, EC_{ss} was almost constant at 10 and 45 cm, while the volumetric water content increased from 0.197 to 0.351. This caused 0.22×10^3 $\text{cm}^3/\text{cm}^3\text{h}$ increase in uptake rate. Also, EC_{ss} was constant at 5 and 45 cm in column K, while by increasing 0.13 cm^3/cm^3 water content the uptake rate showed even a slight reduction. A small change of θ at 20 to 25 cm of column K increased the S by almost 3 times. An interesting observation as can be seen in columns J and K at 15 cm is that at constant EC_{ss} and θ , the uptake rate demonstrates a significant change. Such considerable variation in S also can be seen in columns J and L at 20 cm depth. This can be related to the different evaporative demand of the columns under which the data were collected (see T_p values for different columns). Thus, if the soil water content remains high enough, the evaporative demand is one of the prime factors to control the uptake rate. From all the observations reported in Table 1 and some other non reported data here, it is obvious that at given water content most of water was taken from the less saline parts of the root zone, but the water uptake from other compartments with higher salinities was never stopped. These observations are much close to the algorithm used in numerical simulation models than three other integration ideas.

The magnitude of uptake rate changes per unit salinity was not unique for the reported data. These are shown in Fig. 1c, in which the uptake rate is given as function of each soil salinity compartment. Irrespective of the general shape of the figure, the scatter indicates that beside soil salinity some other factors are influencing the uptake rate; mainly evaporative demand and root activity. To separate the effect of evaporative demand from other factors, the S values for each independent column as function of in-point EC_{ss} are given in Fig. 2; the scatter is much less than that of Fig. 1c. However, Fig. 2 demonstrates the condition under which the evaporative demand was nearly constant for each independent soil column. Looking at this figure, still some scatter can be observed. We assume that this may point the dynamic change of root activity during the

stress period. From our reported data, one may conclude that the root activity is inconstant during the stress period (Fig. 1a). Probably, one of the major reasons for this is the change in root hydraulic conductivity. The osmotic adjustment can be also regarded as a reason for the dynamic change of root activity during the stress period. This may also explain the reason for non-unique response of water extraction rate under similar matric and osmotic potentials. While roots may adjust to salinity, there seems to be no apparent adjustment for water stress. Also, this may explain the reason for some discrepancies in the numerical simulation models that deal with root water uptake under salinity stress. Because, in those models the root activity is usually assumed to be constant during the stress period. Although these observations can explain some mechanisms involved in adjusting plant water extraction under saline environment, the magnitude of each remains to be verified in more details.

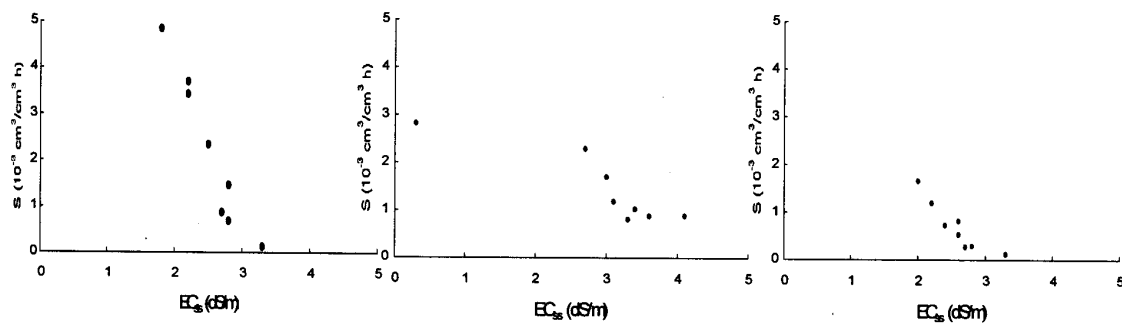


Figure 2. The uptake rate versus in-point EC_{ss} under relatively constant evaporative demand.

From the presented data, we may conclude that under real conditions plants tend to minimize the energy needed to overcome the osmotic head of the soil water. This means that plants tend to take up water from the depth with the minimum salinity and minimize the uptake from other parts as long as the zone with minimum salinity contains enough water to provide the evaporative demand. When this zone can no longer satisfy the evaporative demand, the major amount of water will be taken up from the next less saline depth. This process continues until the free energy of the soil water due to high salinity decreases to such an extent that the biological energy of the plants has become insufficient and water uptake stops altogether. When plants take up water from one depth (because of lower salinity) the water moves from another depth with higher water content due to the soil hydraulic head gradient. The soil solution salinity may or may not change due to the transported water at that depth, compared with that before root water uptake. But, the salinity at the depth from which the water was taken up will certainly increase if the water is not replenished from another depth. Thus, at a certain time and depth EC_{ss} may change or remain unchanged due to root water uptake. Therefore, the dynamic change of water uptake patterns under stress period as shown in this paper indeed resembles many mechanisms that act simultaneously in the root zone. As long as the influence of each independent responsible mechanism is not fully understood, the quantitative description of plants water integration remains complicated enough to be verified. More detailed experimental studies are still needed to gain such quantitative description.

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