

## Relationship Between Root Uptake-Weighted Mean Soil Water Salinity and Total Leaf Water Potentials of Alfalfa

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**Summary.** Alfalfa was grown in five laboratory soil columns and irrigated at a fixed average amount per day. One column received tapwater at 6-day intervals; the others saline water ( $h_o = -12$  m) at intervals of 4, 6, 8, and 12 days. The alfalfa was harvested at 24-day intervals. The resulting widely varying distributions of soil water content, pressure potential and osmotic potential were measured in detail. From these data variously weighted mean soil water potentials were calculated and correlated with measured total leaf water potentials. This indicated that in the moist, saline soil columns the alfalfa plants tended to maximize the root uptake-weighted mean total soil water potential and, since the pressure potentials were generally high compared with the osmotic potentials, also the uptake-weighted mean osmotic soil water potential (minimize the uptake-weighted mean salinity). For the drier nonsaline soil column the leaf water potentials were much lower than expected from the soil water retention function. This was attributed to dominant resistance for water flow through the soil and across the soil-root interface.

Plants absorb only a small fraction of the minerals dissolved in irrigation water and only pure water evaporates from the soil surface. As a result, in arid and semi-arid regions soluble salts accumulate in irrigated soils and reduce crop yields, unless they are removed by excess irrigation. In many areas, water needed for adequate leaching is not available; salt concentrations increase downwards and can become high enough that some salts precipitate. The effects of root zone salinity on crop yields have been studied mostly with nearly uniform salt distributions, either in salt solutions or in soils irrigated with high leaching. Under most field conditions plants interact and adjust to water contents and salinities that vary in time and space. Root water uptake distributions depend on prevailing soil water pressure and osmotic potential distributions. These distributions change due to the water and salt fluxes resulting from the existent potential gradients, the current root water uptake distribution, and irrigation management. Crop yields depend strongly on root water uptake, with possibly different effects at different growth stages. Salinity may also affect yields via other physiological functions, e.g. growth regulators.

These complex relationships have caused contradictory reports on how to integrate soil salinity to obtain the best correlation with yield. One group (e.g., Shalhevet and Bernstein 1968; Bower et al. 1969; Ingvalson et al. 1976) reported that crop response should be related primarily to the mean soil salinity and, hence, that yield is affected strongly by the higher salinities in the bottom of the root zone. Another group (e.g. Wadleigh et al. 1947; Lunin and Gallatin 1965; Bingham and Garber 1970; Bernstein and Francois 1973) argued that yields are related better to the upper root zone salinity and/or irrigation water salinity than to deep-root-zone salinity. A corollary to the latter position is that yields are determined by some weighted mean salinity, perhaps the uptake-weighted mean salinity (Bernstein and Francois 1973; Raats 1974).

To enhance the understanding of these complex interrelationships, involving the dynamic behavior of living plants, alfalfa was grown for more than 2 years in densely instrumented laboratory soil columns and harvested at about 24-day intervals. Soil water content, pressure potential and osmotic potential distributions in the root zone were measured in great detail and were varied by varying the quantity and salinity of the irrigation water, as well as the irrigation frequency. Leaf water potentials were measured as well. This paper reports correlations found between total leaf water potentials and variously weighted mean soil water potentials.

## Theory

Water flowing through plants passes through semi-permeable membranes. Therefore, the flux density is proportional to the gradient of the total water potential

$$h_t = h_p + h_o + h_g, \quad (1)$$

where the subscripts *t*, *p*, *o*, and *g* refer to total, pressure, osmotic, and gravitational, respectively. Later, the subscripts *s* and *l* are added to distinguish between water in soil and leaves, respectively. Water potentials are expressed as head ( $JN^{-1} = m$ ; Koorevaar et al. 1983), even though the density of the soil solution varied slightly with solute concentration. Deviations from the assumed density of  $1,000 \text{ kg m}^{-3}$  have no consequences for these essentially one-dimensional experiments and are within the overall accuracy of the measurements.

The osmotic head  $h_o$  represents only the contribution of solutes in bulk solution. When the solutes can move freely with the water, the flux density depends only on differences in hydraulic head

$$h_h = h_p + h_g = h_p - z, \quad (2)$$

where  $z$  = vertical coordinate, positive downward (*m*). One-dimensional, vertical flow of water in unsaturated soil is described by Darcy's law

$$q = -k[\theta] \frac{\partial h_h}{\partial z} = -k[\theta] \left( \frac{\partial h_p}{\partial z} - 1 \right) \quad (3)$$

and the continuity equation

$$\frac{\partial \theta}{\partial t} = - \frac{\partial q}{\partial z} + \lambda[z, t], \quad (4)$$

where  $q$  = water flux density ( $\text{m}^3 \text{m}^{-2} \text{s}^{-1} = \text{m s}^{-1}$ ),  $k[\theta]$  = hydraulic conductivity as function of volume fraction of water  $\theta$  ( $\text{m}^3 \text{m}^{-3}$ ),  $t$  = time (s), and  $\lambda[z, t]$  = (negative) rate of water uptake by roots ( $\text{m}^3 \text{m}^{-3} \text{s}^{-1}$ ).  $\lambda[z, t]$  depends on such variables as osmotic and pressure head distributions, root characteristics and evaporative demand.

A main objective of this study was to investigate the dependence of  $\lambda$  on non-uniform soil water osmotic and pressure head distributions. One approach to obtain values for  $\lambda$  is to measure  $\theta$ - and  $h_h$ -distributions at various times. From the former one can calculate  $\partial\theta/\partial t$  distributions, and from the latter, together with a  $k[\theta]$ -function, one can calculate  $\partial q/\partial z$ -distributions with (3). Substitution of the results in (4) then yields  $\lambda$ -distributions. Unfortunately, due to a few extreme drying cycles the soil columns had become somewhat inhomogeneous, causing absolute values of  $\theta$  to vary enough for this inherently inaccurate procedure (Flühler et al. 1976) to yield useless  $\lambda$  values. It is much more accurate to select time periods during which  $\partial q/\partial z \simeq 0$ , so that

$$\lambda \approx \frac{\partial\theta}{\partial t}. \quad (5)$$

This approximation was used with data obtained at least two days after an irrigation (c.f. field capacity).

The study of plant reactions to nonuniform, varying soil water potentials would be greatly enhanced if one could measure root water potentials. Unfortunately, experimental methods to do this are almost entirely lacking; leaf water potentials are much easier to measure. Plant water potentials depend on the soil water potential distribution, as well as on the evaporative demand of the atmosphere, the size of the canopy and the plant resistances in the transpiration stream. The environmental conditions were nearly constant throughout the entire experimental period; only the illuminance decreased somewhat with time. The actual evapotranspiration increased during each growth period with canopy size (with ample water supply). There were indications (Dirksen and Raats 1984) that the longitudinal plant resistances in the transpiration stream were much smaller than the radial resistances of the roots. Since all leaf water potentials were measured while there was an abundance of roots throughout the soil columns, the differences between root water potentials and leaf water potentials must have been relatively small. All total leaf water potentials used were measured within a few days before each harvest when canopies were large and the potential evapotranspiration was about the same.

The above considerations are meant to justify the assumption that the leaf water potentials reflected the integration by the alfalfa plants of the various nonuniform soil water potential distributions. Consequently, measured leaf water heads were correlated with various averages of the soil water heads. The uptake-weighted mean osmotic head  $\tilde{h}_{\text{os}}$  of the soil water can be defined as

$$\tilde{h}_{\text{os}} = \int_0^{\infty} \lambda[z] h_{\text{os}}[z] dz / \int_0^{\infty} \lambda[z] dz, \quad (6)$$

where  $h_{\text{os}}[z]$  is the osmotic head of the soil solution at depth  $z$ . Since the direct evaporation from the soil surface was negligible, the denominator is equal to ET.

Similarly, the uptake-weighted mean total head  $\tilde{h}_{ts}$  can be defined as

$$\tilde{h}_{ts} = \int_0^{\infty} \lambda[z] h_{ts}[z] dz / \int_0^{\infty} \lambda[z] dz. \quad (7)$$

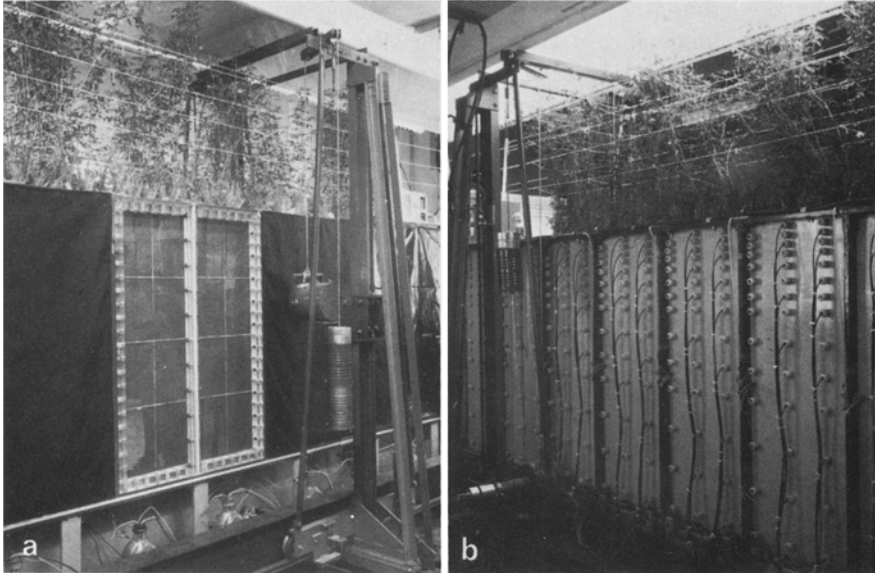
Unfortunately, the data files were erased before the need for  $\tilde{h}_{ts}$  was realized. Since  $\tilde{h}_{os}$  and the uptake-weighted mean water content  $\tilde{\theta}$  had been calculated the following approximation was used

$$\tilde{h}_{ts} = \tilde{h}_{os} + \tilde{h}_{ps} \approx \tilde{h}_{os} + h_{ps}[\tilde{\theta}]. \quad (8)$$

The error introduced by (8) should be small enough to have no influence on the qualitative results.

## Experimental

The experiments were carried out in six segments ( $0.394 \times 0.178 \times 1.07$  m) of the soil water-flow model with two-dimensional automatic gamma ray attenuation scanner described by Dirksen and Huber (1978). The front walls of the segments consisted of 9.5 mm-thick glass plates through which soil packings, wetting fronts and roots could be observed (Fig. 1 a). The glass walls were covered with black cloth to keep the roots in the dark. The back walls were made of 9.5 mm-thick aluminum plates through which tensiometers and salinity sensors were inserted (Fig. 1 b).



**Fig. 1a and b.** Experimental apparatus. **a** Front view with exposed glass plates of two columns; gamma source and suction bottles for drainage water. **b** Back view with aluminum walls, salinity sensors, tensiometers and gamma detector

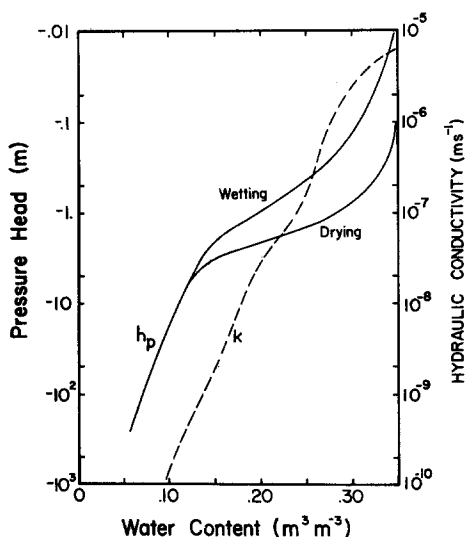


Fig. 2. Soil water retention function and hydraulic conductivity function of Pachappa very fine sandy loam

The segments were packed with Pachappa very fine sandy loam (52.4% sand, 39.5% silt and 8.1% clay) at a bulk density of about  $1,570 \text{ kg m}^{-3}$ . A representative soil water retention function  $h_p[\theta]$  and hydraulic conductivity function  $k[\theta]$  of these soil columns are presented in Figure 2. Soil water contents were measured with the gamma scanner across the 0.178 m dimension. The depth increment varied from 1 cm at the top to 5 cm at the bottom. All water contents used are averages of three vertical scans per soil column, normally with a relative accuracy within  $\pm 0.002 \text{ m}^3 \text{ m}^{-3}$ .

Alfalfa was grown in the soil columns. At first they were irrigated daily, and leaf water potentials were measured only occasionally with psychrometers. These measurements, as well as calculations of  $\partial q/\partial z$ , were very inaccurate. After destructive sampling of one column, the remaining five were irrigated at intervals ranging between 4 and 12 days, and total leaf water potentials were measured with a pressure chamber towards the end of each 24-day growth period. Since these measurements were much more accurate and (5) could be used, the experimental conditions and results of this later phase of the study are reported only.

The columns were irrigated at an average dose of 14.3 mm per day at an interval, in the order of their position, of 6, 4, 8, 12, and 6 days (indicated as A-6, B-4, C-8, D-12, and E-6), respectively. Column A-6 received tap water with an osmotic head  $h_o = -2.4 \text{ m}$ ; columns B-4 through E-6 received irrigation water with  $h_o = -12.0 \text{ m}$ , obtained by adding equal molar (charge basis) quantities of NaCl and  $\text{CaCl}_2$ . Before packing, phosphate was added to the soil at a rate of 5.2 g P per kg. The irrigation water, with small amounts of K, Mg,  $\text{NH}_4$  and Ca nitrate and phosphate, was pumped at rates preventing ponding through 14 open-ended fine plastic tubes distributed over the soil surface of each column. Two parallel ceramic tubes (13 mm OD) at the bottom of each column collected drainage water under partial vacuum; volume and electrical conductivity (EC) usually were measured

daily. The EC of the soil solution was measured in-situ with salinity sensors (Model 5100, Soilmoisture Equipment Company, Santa Barbara, California, USA). They were located in two vertical rows (Fig. 1b) at depth intervals ranging from 3 cm at the top to 15 cm at the bottom. A total of 100 salinity sensors could be read automatically in about 40 min. All EC values were converted to osmotic head according to  $h_{os}(m) = -4 \text{ EC (dS m}^{-1}\text{)}$ .

Home-made tensiometers identical in size to the salinity sensors were used to measure soil water pressure heads in the same rows of measuring positions. The pressure heads used for this study were measured with an accuracy of a few millimeters of water with only eight tensiometers, each connected to a servo-pressure sensor (Model 314D, Sundstrand Data Control, Inc., Redmond, Washington, USA). The tensiometers were moved from column to column as needed. The gamma scanner, salinity sensor, and tensiometer data were all recorded automatically on punched paper tape, transferred with an optical tape reader to floppy discs, and processed and analyzed with a programmable desk-top calculator and plotter.

Fluorescent lights were mounted in a box with a thin tedlar sheet at the bottom, about 0.80 m above the soil surface. These lights (Vita-Lite, Duro-Test Corp., North Bergen, NJ) are designed specifically for plant growth and do not require additional incandescent lights. The temperature in the box was controlled by forced, cooled convection at 25 °C to keep the heat of the lamps away from the plants and to increase the illuminance. The illuminance in the canopy was also increased by reflecting shades hung from the edge of the lights to a point below the soil surface. To enhance evapotranspiration, air was blown from outside the reflecting shades through a perforated tube into the canopy. The lights were on for 12 h per day. At the beginning of this study period the illuminance varied from about 18 K lux at 0.15 m to 27.5 K lux at 0.60 m above the soil surface; at the end these values were 14.5 and 20.5 K lux, respectively.

The alfalfa had a density of 230 plants per m<sup>2</sup> and generally looked healthy. Plant analyses showed normal mineral contents. The alfalfa grew to 0.60 m height and was cut every 24 days at 0.12 m above the soil surface to promote quick regrowth. The canopy was confined by twine, but its cross-sectional area near the top was still about 2.5 times that of the soil surface. As a result, the maximum rate of evapotranspiration (ET) was around 1 mm per h. The room was air-conditioned and its temperature was around 25 °C day and night. The relative humidity occasionally reached 80% in the light, while in the dark it was usually around 50%.

During the last few days of each growth period total leaf water potentials  $h_{tl}$  were measured with a pressure chamber (Plant Water Status Console, Model 3005, Soilmoisture Equipment Co., Santa Barbara, California, USA). Six replicate measurements generally varied only within a few meters. Each measurement was made on the common stem of an end cluster of alfalfa leaves that were exposed to direct light. To reduce the experimental error, the cluster was wrapped immediately in moist paper tissue and the protruding end of the stem was kept as short as practicable (Millar and Hansen 1975).

At the end of the experiments the columns were sampled in various ways to determine bulk densities, soil hydraulic properties and/or root distributions. Soil water contents and salinities were also determined to check the gamma scanner and salinity sensor data.

## Results and Discussion

The root length density in the column sampled at the end of the daily irrigation period (260 days) – prior to the study in the remaining columns reported here – was the highest ( $13 \times 10^4 \text{ m m}^{-3}$ ) at about 0.10 m depth, and decreased to a fairly uniform value of about  $3 \times 10^4 \text{ m m}^{-3}$  below 0.35 m; close to the bottom it increased again to  $5 \times 10^4 \text{ m m}^{-3}$ . Final destructive sampling of the other columns indicated that root length densities everywhere had at least doubled. Therefore, at the time of the measurements used in this paper, roots were abundant throughout the columns.

Osmotic head profiles in column B-4, C-8, and D-12 (Fig. 3) near the end of the study period illustrate the general principle that salinity increases faster with depth as the irrigation frequency increases, resulting in a higher average salinity (Rawlins and Raats 1975; Dirksen 1983). The profiles are not smooth; they are based on just one salinity sensor reading per depth. Detailed destructive sampling showed appreciable spatial variability of salinity. Salinity sensor readings taken just prior to the sampling agreed well with in situ salinities derived from chloride concentrations of supernatants of soil-water mixtures, indicating that the salinity sensors were functioning properly. Often salinity sensors temporarily deviated from the general trend. This may have been caused by active roots in close proximity of such a sensor.

Figure 4 shows water content profiles in column C-8 during the last 8-day irrigation interval of a 24-day growth period. Profile 1, near the end of the 16-h irrigation, and profile 2, about 16 h later, indicate appreciable redistribution. Profiles 3, 4, and 5 were measured during the dark periods delineating day 6 and 7 and profile 6 was at the time of harvest, after 7 h of transpiration on the last day. Drainage had decreased to less than 1 mm/day during the last two days; therefore, the differences between the profiles approximate the root uptake distributions. The water content profile just prior to the start of the irrigation was identical to profile 5 to about 0.30 m depth and nearly equal to profile 6 from 0.40 m downwards. A few irregularities in the profiles were smoothed. These originated during extreme drying and persisted during subsequent wetting (see e.g. Dirksen 1980, Fig. 3). Also, the water content in profile 1 decreases from about 0.20 m depth towards the surface, when one might expect at least uniform water contents (Profile 1 of Fig. 5 indicates

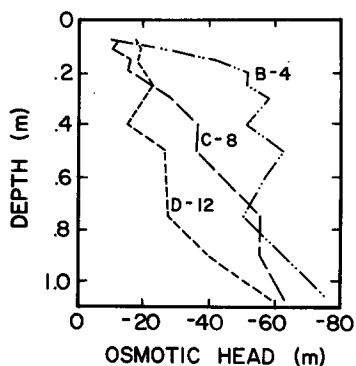


Fig. 3. Osmotic head profiles in column B-4, C-8, and D-12 near end of study period

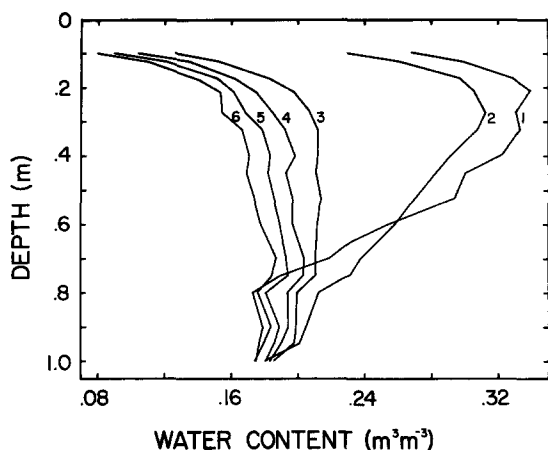


Fig. 4. Water content profiles in column C-8 during last 8-day irrigation interval of a growth period (see text)

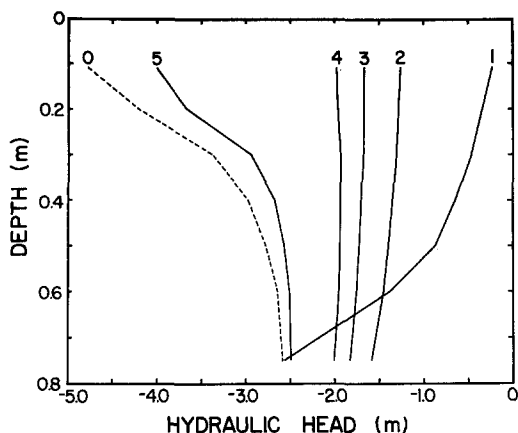


Fig. 5. Hydraulic head profiles for same irrigation interval as in Figure 4 (see text)

a slight increase in pressure head towards the surface). Most likely, this must be attributed to root crowns up to 15 mm thick. The volume occupied by these root crowns was not available to the percolating irrigation water and reduced also subsequent water contents. Despite these irregularities changes in water content over relatively short time periods could be determined very accurately. Water content profiles such as in Figure 4 were measured throughout the experimental period from which root uptake distributions could be determined according to (5).

The hydraulic head profiles in Figure 5 were measured during the same irrigation interval as in Figure 4. The time of profiles 1 and 2 was the same as in Figure 4, profile 0 existed before the start of irrigation. Profiles 2, 3, and 4 were measured before the start of transpiration at the day with the same number; profile 5 occurred after 8 h of transpiration on day 7 (The gamma and tensiometer measurements covered different time periods). When hydraulic heads were not measured directly, they could be derived from the soil water contents and the soil water retentivity function (Fig. 2). Data such as in Figures 3, 4, and 5 were



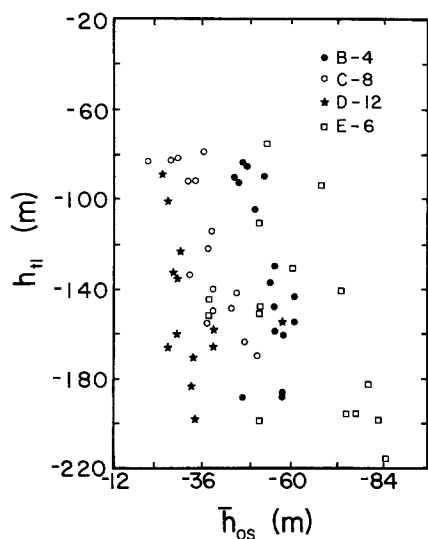


Fig. 6. Total leaf water heads vs. average osmotic heads of middle third of soil columns

measured throughout the study period. From these variously weighted soil water potentials were calculated and then correlated with measured total leaf water potentials.

First, total leaf water heads  $h_l$  were correlated with the average water content  $\bar{\theta}_s$  and average osmotic head  $\bar{h}_{os}$  of various depth intervals of the soil columns. One could reason, for example, that the correlation between  $h_l$  and  $\bar{h}_{os}$  should be best for an intermediate depth interval, since the  $\bar{h}_{os}$  values in the upper zones were dominated by the rather high  $h_o$  values of the irrigation water, and those in the lower zone were too low for significant water uptake. However, no such correlations were found. For example, there was no clear relationship between  $h_l$  and  $\bar{h}_{os}$  in the middle third depth intervals (Fig. 6). Reasonably good correlations were obtained between  $h_l$  and  $\bar{h}_{os}$  values for entire columns individually, but not for all columns lumped together (Fig. 7). Salinities differed appreciably with irrigation frequency, but per column  $\bar{h}_{os}$  was quite insensitive to changes in osmotic and pressure head distributions that caused large variations in  $h_l$ .

The  $h_l$  values of Figure 7, plotted against the uptake-weighted mean osmotic head  $\tilde{h}_{os}$  calculated according to (5) and (6), coalesce remarkably well (Fig. 8) considering that  $\tilde{h}_{os}$ , unlike  $\bar{h}_{os}$ , was quite sensitive to errors in the measured rates of change of water content. Moreover,  $\tilde{h}_{os}$  could vary considerably over short time periods, while  $\bar{h}_{os}$  varied only slowly in time. This difference between  $\bar{h}_{os}$  and  $\tilde{h}_{os}$  is also illustrated by their range in values. For instance, in column E-6  $\bar{h}_{os}$  varied between about -50 m and -70 m, whereas  $\tilde{h}_{os}$  varied from about -27 m to -82 m. The solid curve in Fig. 8 was fitted visually to the data points. It shows a very steep decrease of  $h_l$  from -80 m to -160 m around  $\tilde{h}_{os} = -36$  m ( $EC = 9$  dS m<sup>-1</sup>). The value at the ordinate reflects that during light periods  $h_l$  was seldom higher than -60 m, even at high values of  $h_{ps}$  and  $h_{os}$ . The other end of the curve reflects that at low values of  $\tilde{h}_{os}$ ,  $h_l$  was limited to values of about -200 m, most likely due to closure of the stomates. The highest  $h_l$  values of column B-4 are somewhat high to

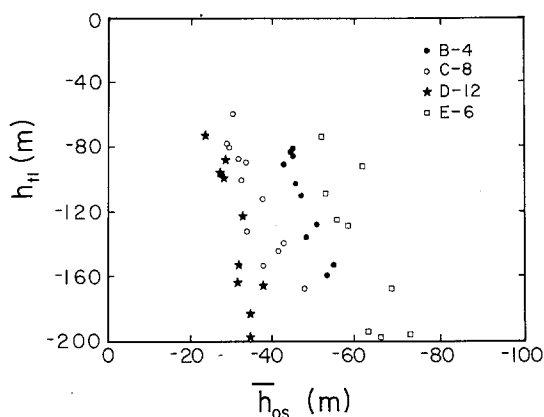


Fig. 7. Total leaf water heads vs. average osmotic heads of entire soil columns

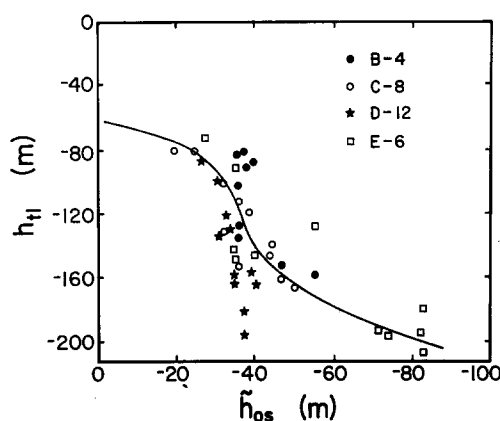


Fig. 8. Total leaf water heads vs. uptake-weighted mean osmotic heads

fit the curve. The rather frequent irrigation of this column increased salinity rapidly with depth (Fig. 3), keeping  $\tilde{h}_{os}$  relatively low even when there was enough water available to allow  $h_l$  to be near its maximum value. The lowest  $h_l$  values of column D-12 deviate appreciably from the curve. Even when this relatively low saline column dried out to the point that the plants started wilting ( $h_l \approx -200$  m),  $\tilde{h}_{os}$  still was higher than  $-40$  m. Under those extremely dry conditions the salinity sensors functioned slowly because of poor hydraulic contact with the soil solution. Hence, for the lowest values of  $h_l$  of column D-12 the actual values of  $\tilde{h}_{os}$  most likely were closer to the curve than indicated in Figure 8.

The above reasoning suggests that  $h_l$  should correlate even better with the uptake-weighted mean total head,  $\tilde{h}_{ts}$ , calculated according to (8). The low values of  $h_l$  for column D-12 and the high values of  $h_l$  for column B-4 indeed fall much closer to the curve in Figure 9 than in Figure 8. The two curves differ little from each other because most absolute values of  $h_{ps}$  were small compared to those of  $h_{os}$ . This was not true for column A-6 irrigated with tapwater, for which  $\tilde{h}_{ts}$  values are also plotted in Figure 9. These all fall below the curve for the saline columns, except the highest value. The soil water retention function (Fig. 2) indicates that  $h_{ps}$  re-

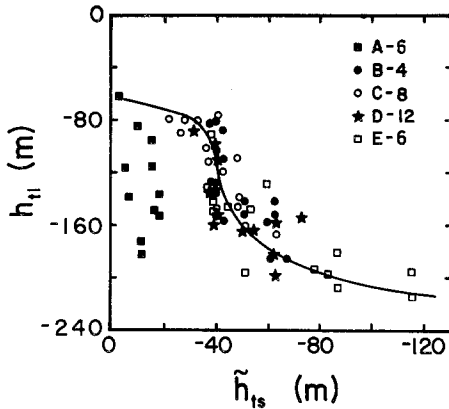


Fig. 9. Total leaf water heads vs. uptake-weighted mean total heads

mained above  $-5$  m down to  $\theta = 0.125 \text{ m}^3 \text{ m}^{-3}$ , and was still only  $-50$  m at the lowest observed water contents of  $0.08 \text{ m}^3 \text{ m}^{-3}$ . Apparently, low values of  $\tilde{h}_{ps}$  had an effect on  $h_{il}$  much larger than their own value. This, no doubt, reflects increasing soil resistance (Reicosky and Ritchie 1976), but could also be due to an extra resistance associated with low water contents at the soil-root interface (Herkelrath et al. 1977; Harley and Scott Russell 1979). The saline columns remained too wet for this effect on  $h_{il}$  to become noticeable.

Even with negligible experimental errors, a perfect correlation between  $\tilde{h}_{os}$  or  $\tilde{h}_{ts}$  and  $h_{il}$  should not be expected. The energy that must be expended to sustain the transpiration stream, which is reflected in the value of  $h_{il}$ , depends not only on the prevailing soil water osmotic and pressure head distributions, but also on the actual magnitudes and locations of the hydraulic resistances in the transpiration stream. If plants were to take up the same amount of water against the same values of  $\tilde{h}_{os}$  and  $\tilde{h}_{ts}$ , but at different locations in the root zone,  $h_{il}$  would vary with the distribution of the plant resistances in each pathway. If the differences between these resistances were negligible so that plants could take up all the water needed with equal ease at any single depth in the root zone, maximizing  $\tilde{h}_{os}$  would mean that  $h_{os}$  would tend to be uniform throughout the root zone. Any water with a higher  $h_{os}$  value, for example from irrigation, would be taken up first until it reached the same  $h_{os}$  value as in other parts of the root zone. Such a pattern of water uptake appears to be approached locally by the very small (fractional) uptake in the bottom of a root zone under frequent irrigation, but will in general soon be limited by the flow of water in the soil towards the root.

A comparison of Figures 6 and 9 and the above considerations indicate that in the intermediate ranges of salinity and water content in this study, alfalfa plants took up water according the distributions that kept the uptake-weighted mean total head as high as possible. Because the pressure heads in the saline columns generally were high compared to the osmotic heads, essentially the same conclusion follows for the uptake-weighted mean osmotic head; that is, the plants minimized the uptake-weighted mean salinity.

In the introduction the influence of root zone salinity on crop yields was discussed. These experiments were not suited to investigate this relationship,

because there were no treatment replications and yields were sometimes influenced by incidental causes. However, since leaf water potentials are an indication of actual evapotranspiration, and the latter, in turn, is related to crop yields via the transpiration ratio the results reported here may be considered to support the hypothesis that crop yields are related most directly to uptake-weighted mean soil water potentials.

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