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Patterns of Water Uptake and Root Distribution of Soybeans (*Glycine max.*) in the Presence of a Water Table[1]

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ABSTRACT

The increasing importance of water use in crop production has demonstrated the need for integrated studies of water transport phenomena in the soil-plant-atmosphere system. A better understanding of the basic principles involved can lead to better management techniques for efficient water use. The purpose of this work was to measure water uptake patterns of soybeans (*Glycine max.*) and relate these to root distribution and water uptake per unit root length.

Water uptake in soil columns was analyzed using the flow equations for water movement in the soil, treating the root system as a macroscopic sink. The sink term represents the volume of water removed by the roots from a known volume of soil per unit time. Two soil columns were analyzed periodically for water content, root weight, and root length. Graphical evaluation of the water content and soil water flux distributions as a function of depth and time permitted determination of the sink term.

The results indicated that in the presence of a water table, water uptake was not necessarily related to root distribution and that a small amount of roots near the capillary fringe absorbed most of the water. The results also showed the combined importance and interaction of the hydraulic conductivity and the root distribution in determining the magnitude and the distribution of the sink term. Both of these factors limited the rate of uptake. As the plants grew, both increased water uptake per unit root length and increase in the length of roots contributed to meeting the rising daily rate of water use.

Additional index words: **Sink strength.**

THE importance of water in plant growth has prompted the study of the mechanism of soil water uptake by plant roots. Several models have been proposed that are based on mathematical solutions for the soil water flow equation to a single root (1, 3, 4). This approach to water uptake has been moderately successful in describing water uptake by individual roots (4). In contrast to this microscopic approach, models presented by Whisler et al. (13) and Rose and Stern (12) employ a macroscopic approach for analyzing water uptake by root systems. In the macroscopic approach water uptake is inferred from measurement of soil properties.

This report presents data on water uptake patterns of soybeans grown in soil columns and shows the utility of the macroscopic approach in analysis of water uptake by root systems, using the model of Whisler et al. (13). Sink profiles, which were used to infer water uptake, are compared with root density profiles for soybeans (*Glycine max.*) grown in soil columns.

METHODS AND MATERIALS

Soybeans were grown in soil columns 122 cm by 10.2 cm in diameter. The columns were made of polyvinyl chloride drain pipe and filled with lower horizons of a Dickinson sandy loam. The soil contained 74% sand, 16% silt, and 10% clay and had a cation exchange capacity of 4 meq/100 g. Air-dry soil was sieved through 710-μ openings (U.S. Standard Sieve Series No. 25) and poured into the column through a funnel attached to a tube that extended to the bottom of the column. While soil was being poured into the column, the column was gently tapped and rotated until full. The soil was uniformly packed into the columns to give an average bulk density for the whole column of approximately 1.60 g/cc. The final bulk density of all columns ranged from 1.54 to 1.63 g/cc.

Soil columns were initially wetted with 2 liters of deionized water. A water table was maintained 100 cm from the soil surface by a mariotte bottle arrangement, which supplied water through the bottom of the column in the form of a half-strength standard Hoagland's solution. The columns were sealed with plexiglass discs to prevent evaporation, and were allowed to equilibrate for 4 weeks before planting.

Columns were then placed in a specially designed growth cabinet in which soil temperature was maintained at 25.0 ± 0.5 C throughout the experiment. The lower part of the growth cabinet, containing the soil columns, was completely enclosed and partitioned from the upper part, which contained aerial portions of the plant. This arrangement provided good control of the soil temperature; however, no attempt was made to control the temperature and the humidity of the aerial environment. Air temperature ranged from 20 C during the night to 30 C during the day. Light was provided by a combination of Lucalox lamps (Lu-400) located about 120 cm above the soil surface and by cool white fluorescent lamps placed vertically between the plants. This arrangement gave an intensity of 0.37 langley per min (.4 to .7μ wavelength band) 15 cm above the soil. Daylength was 14 hours.

After the columns had equilibrated for 4 weeks, three soybean seeds of the variety 'Clark' were planted in all columns except the control. A small amount of soil was removed through the top of the column with a cork borer, and seeds were placed 2 cm in the soil. Soil that had been removed was then carefully packed over the seeds. After emergence, plants were thinned to a single plant per column. Ten days after planting, a small piece of foam rubber was wrapped around each plant stem, completing the seal in the plexiglass plate and preventing evaporation from the soil surface. All plants showed normal growth throughout the experiment.

Twenty-four days after planting, two columns were removed from the growth cabinet. Plant tops were cut off at the soil surface and weighed. Soil columns were cut into 10-cm lengths and samples were taken for water content. The remainder of the soil was carefully washed from plant roots with a stream of cold water. After the roots were washed, they were spread uniformly over the bottom of a black tray. They were photographed, blotted dry, and weighed. Both tops and roots were dried overnight at 70 C and weighed.

Root length was determined from photographs by the line intercept method described by Reicosky et al. (11). In this work 300 random locations, rather than the average of three sets of 100 random locations, were used to estimate root length. The slide was then reversed, and the same 300 random locations were used for the second estimate of root length. Root lengths in a given depth increment of a column are averages of both estimates.

Further harvests and analyses were made on pairs of columns 38, 52, 59, 66, and 73 days after planting. Soil water distribution in the control column (without a plant) was measured at the end of the experiment in the same manner as in the other columns. It was assumed that soil water profiles in all columns were initially the same, and that observed differences as a function of time resulted from water absorption by the plants.

The model of Whisler et al. (13) assumes the Darcy equation for unsaturated flow is valid and given by

$$v = -K(\tau)\nabla H \quad [1]$$

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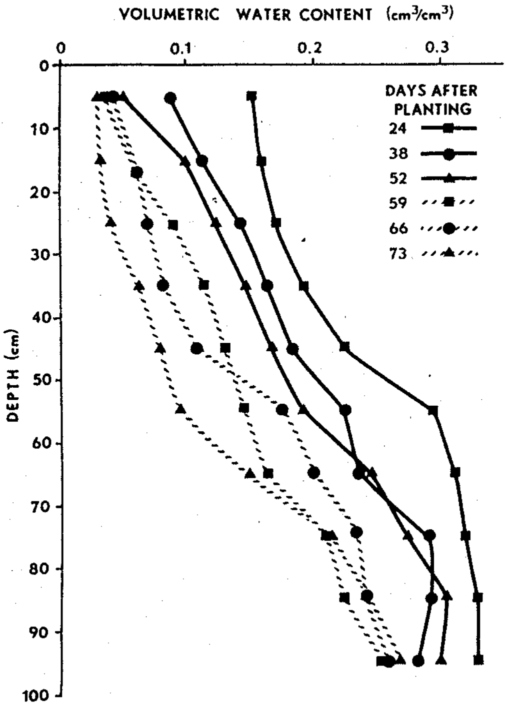

Fig. 1. Water content profiles at various times after planting. Each curve represents the average of two columns analyzed at the specified time.

where v is the soil water flux, ∇H is the gradient of hydraulic head, $K(\tau)$ is the hydraulic conductivity of the soil as a function of suction τ. The hydraulic head is the sum of the gravitational and pressure heads, both expressed in length units. When the conservation of matter principle is imposed, the equation for vertical flow is

$$\partial\theta/\partial t = -\partial v/\partial z + S \qquad [2]$$

where θ is the volumetric water content, t is time, v is the soil water flux in the z direction (z is positive downward), and S is a sink term that represents water uptake by plant roots. The sink term is the volume of water extracted from a unit volume of soil per unit time. The sink term was calculated by graphical evaluation of the other two terms in equation [2].

The relationship between volumetric water content and depth as a function of time is shown in Fig. 1. Since soil columns were analyzed in 10-cm segments, the mean value of the depth increment was used to specify the depth-water content relationship. Values of $\partial\theta/\partial t$ were obtained from a graph of water content vs time at different depths using the data shown in Fig. 1. Eye-fitted curves were drawn through data points for each depth, thus providing a family of curves for various depths. The slope was determined at the time of analysis for each depth.

Values of $\partial v/\partial z$ were determined graphically from a plot of soil water flux vs depth at different times. In the upper portion of the columns, v was calculated from the relationship

$$v = K(\tau)\ \partial\tau/\partial z + K(\tau) \qquad [3]$$

where $K(\tau)$ is the hydraulic conductivity as a function of suction, and τ defined as positive in the unsaturated soil and expressed in cm of water ($\tau = -h$, where h is pressure head). The value of $\partial\tau/\partial z$ was determined graphically from a plot of suction vs depth. Because the bubbling pressure of the tensiometers in the upper part of the columns was exceeded early in the experiment, suction was inferred from the moisture desorption curve shown in Fig. 2. The desorption curve was determined on a pressure plate apparatus. Hydraulic conductivity, $K(\tau)$, was calculated from $K(\theta)$ data obtained using the method of Millington and Quirk (8, 9) as modified by Kunze et al. with the assumption of negligible hysteresis (7). A saturated conductivity of 45 cm per day was determined using a constant head permeameter. The matching factor was 0.0194. Hydraulic conductivity vs water content is shown in Fig. 3.

Because of the difficulty in graphically estimating $\partial\tau/\partial z$ near the water table and the uncertainty as to the water content-suction relationship near saturation, soil water flux below the root zone was calculated from the rate of water supply to the

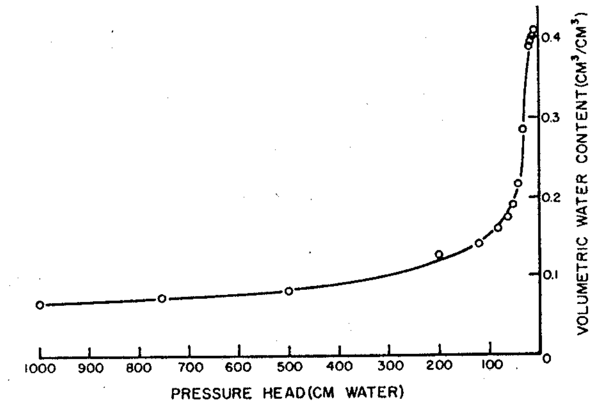

Fig. 2. Volumetric water content vs pressure head for the Dickinson sandy loam soil determined on a pressure plate apparatus.

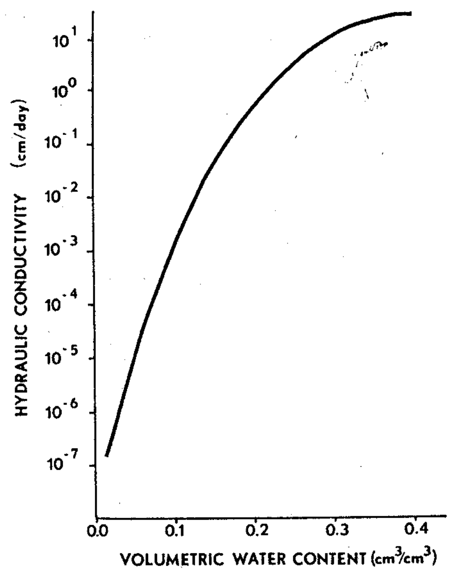

Fig. 3. Hydraulic conductivity vs volumetric water content for Dickinson sandy loam.

water table. Integration of the equation for vertical flow, with respect to time and depth for those regions in which there were no roots, results in

$$\int_{z_1}^{z_2}\int_{t_1}^{t_2} \frac{\partial\theta}{\partial t}\, dzdt = -\int_{z_1}^{z_2}\int_{t_1}^{t_2} \frac{\partial v}{\partial z}\, dzdt \qquad [4]$$

The left-hand side of the equation was evaluated graphically by determining areas between water content profiles between t_1 and t_2 over the depth increment of interest. If one assumes that v is essentially independent of time and can be represented as a time-averaged value, the right-hand side of the above equation can be written as

$$\int_{z_1}^{z_2} d\bar{v} \qquad [5]$$

where $\bar{v}$ is the time-averaged value of the soil water flux defined as

$$\bar{v} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} v\, dt \qquad [6]$$

Thus, soil water flux at any point below the root zone can be calculated from

$$\int_{z_1}^{z_2}\int_{t_1}^{t_2} \frac{\partial\theta}{\partial t}\, dzdt = \bar{v}(z_2) - \bar{v}(z_1) \qquad [7]$$

using data on water supplied to the water table. In this work

$\bar{v}(z_1)$ was the time-averaged flux through the 90- to 100-cm depth increment calculated as the average of rates of inflow at times t_1 and t_2, and $\bar{v}(z_2)$ was the time-averaged flux through the 80- to 90-cm depth increment. Once the left-hand side was evaluated and $\bar{v}(z_1)$ was calculated, the above equation was solved for $\bar{v}(z_2)$. From these time-averaged soil water fluxes, the actual flux at specified times was calculated. Because of the relatively high water content and presence of roots in the 70- to 80-cm depth increment, both methods of calculating soil water flux had limitations for this region. The flux in this region was determined by interpolation between the last reasonable estimates of the flux above and below this depth.

RESULTS AND DISCUSSION

Examples of the soil water flux profiles for 59 and 73 days after planting are shown in Fig. 4. Results from remaining harvests showed similar trends; therefore, data for only these two harvests will be discussed. All results are the average of two columns analyzed on the same harvest day. In earlier harvests plants were not large enough to cause significant changes in the magnitude of sink terms and the soil water flux calculations. The soil water flux in the bottom of the column was 0.4, 1.4, and 6.7 cm/day for days 24, 38, and 52 after planting, respectively. At 59 days after planting the soil water flux in the bottom of the column was about 11 cm/day and decreased sharply in the 50- to 70-cm depth increment. The sharp decrease in soil water flux in this zone was caused primarily by the hydraulic conductivity's dramatic change with depth, as shown in Fig. 5. For example, the hydraulic conductivity changed from 1.5 to 9.0 $\times$ 10^{-3} cm/day in going from the 80- to 90-cm depth increment to the 40- to 50-cm depth increment while the hydraulic head gradient went from 0.8 to 11.0 cm/cm at the same depths. Although the hydraulic head gradient did change in this region, the resulting soil water flux profile was primarily due to the decreasing hydraulic conductivity with decreasing water content (increasing suction). The low hydraulic conductivity above this region resulted in very small soil water flux. The same trend was found in columns analyzed 73 days after planting.

In the early part of the experiment the sink was distributed throughout the upper portion of the columns. The magnitude of the sink was as large as .07 cm^3/cm^3/day at 38 days after planting. At 52 days a maximum sink was observed which showed a progressive shift downward as time passed. Part of this shift was probably due to root growth. Figure 6 presents computations of the sink term as a function of depth. In the latter part of the experiment (at 59 days), the magnitude of the sink was very small in the upper portion of the column, reached a maximum in the 50- to 60-cm depth increment, and decreased at lower depths. The sink profile at 73 days after planting shows a similar trend, with the maximum sink in the 70- to 80-cm depth increment. These results indicate that in the latter part of the experiment maximum water absorption was occurring in the capillary fringe just above the water table. The maximum sink value increased with time, and tended to increase in depth with time. The increase in the sink term with time was related partly to an increase in root density in the same region (see Fig. 7) and partly to an increase in the plant demand for water. The roots in the region of maximum sink activity were white, turgid, and more succulent than those in the upper portion of the column, and were not suberized to any great extent.

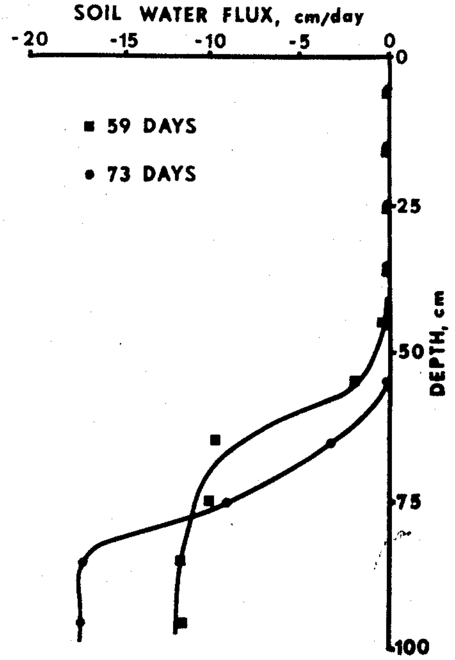

Fig. 4. Examples of the soil water flux profiles as a function of depth at 59 and 73 days after planting.

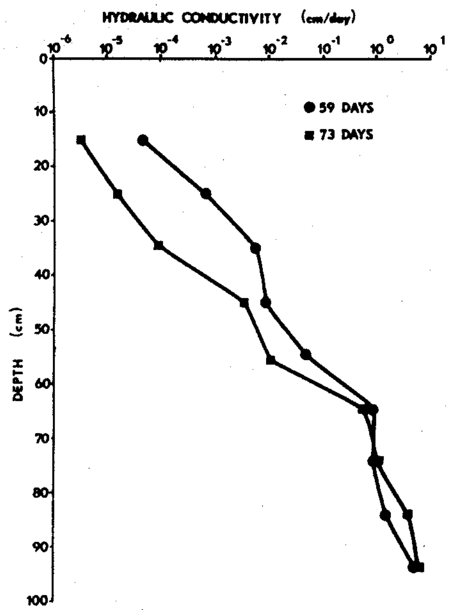

Fig. 5. Hydraulic conductivity vs depth at 59 and 73 days after planting.

Calculation of the sink term from graphical evaluation of slopes involves inherent errors. However, the integrated sink terms ranged from 80 to 97% of daily amounts of water required to maintain the water table, indicating that the calculations gave reasonable results for water uptake. Where the hydraulic conductivity of the soil was low because of low water content, relatively low values for soil water flux resulted. In this situation the magnitude of the sink term, which reflects rate of water extraction by roots, was

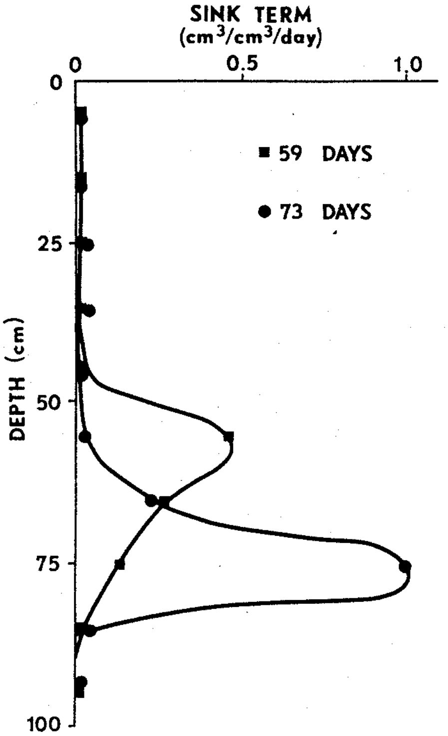

Fig. 6. Examples of the sink term profiles vs depth at 59 and 73 days after planting.

determined primarily by the value of $\partial\Theta/\partial t$. Where the soil was wetter, just above the water table, the value of $\partial v/\partial z$ dominated the magnitude of S.

Marked changes with depth in the relative contribution of $\partial\Theta/\partial t$ and $\partial v/\partial z$ to the value of S were expected in this type of column experiment and for two reasons. First, root growth was limited to essentially one dimension, and the actual rate of downward root growth was probably larger than is true for the field, where lateral root growth is not limited. In addition, the suction was high enough to result in relatively low hydraulic conductivity, but not high enough to limit root growth. Hence, the results suggest that the roots grew downward faster than the water could move up through the soil. As roots grew downward, they extracted a small amount of water and, early in the experiment, this small amount was enough to meet the total demand of the plant. During this period $\partial\Theta/\partial t$ was primarily responsible for the magnitude of calculated values of S. Once the roots reached the capillary fringe later in the growth period, they were able to extract water at much lower suctions and to supply the tops with all the water used.

Second, with the water table maintained at 100 cm, the region between 80 and 100 cm was nearly saturated by capillary rise so that the hydraulic conductivity was near the saturated value. In the zone in which roots extracted water, just above and in the capillary fringe, the sharp decrease in the hydraulic conductivity shown in Fig. 5 caused the soil water flux to decrease markedly, so that $\partial v/\partial z$ was largely accounting for the large values of S. These results confirm the importance of the hydraulic conductivity in the rate of water extraction by plant roots under constant climatic conditions.

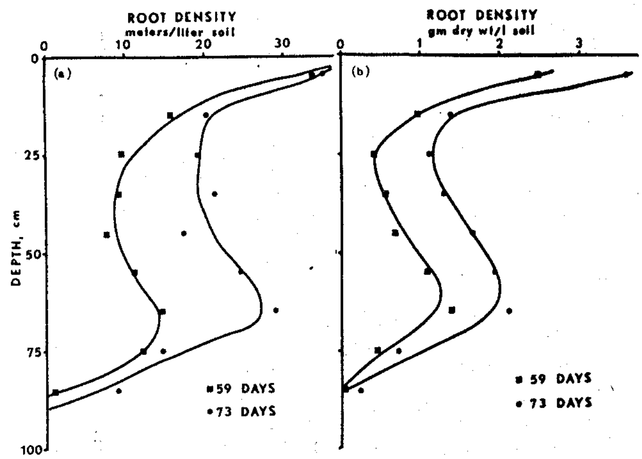

Fig. 7. Root density vs depth at 59 and 73 days after planting. A. length basis; B. dry weight basis.

Table 1. Water uptake per unit root length (cm^3/cm root/day) vs depth.

	Days after planting	
Depth, cm	59	73
0-10	.00042	.000028
10-20	.0026	.00054
20-30	.0034	.0021
30-40	--‡	.0021
40-50	.0057	.0029
50-60	.43	.0097
60-70	.18	.076
70-80	.11	.67
80-90	.023	.035
90-100	--	--

* Value of sink term was positive.

Water uptake per unit root length was calculated by dividing the sink term by the root density (length basis) in that segment of the column (Table 1). The results show that uptake per unit root length was closely related to the sink term. In the upper part of the column where the sink was small, uptake per unit root length was small and increased as the magnitude of the sink increased. This suggests that roots were absorbing water from the region where it was readily available. The results presented in Fig. 5 indicate that the major cause for the decreased uptake per unit root length in the drier parts of the column was more likely related to transmission characteristics of the soil than to root age and suberization. Since the soil was nearly saturated just above the water table, the decrease in uptake per unit length below the zone of maximum uptake per unit root length was probably due to poor aeration. This result suggests that in the presence of a water table, an aeration factor is needed in modeling the sink term in addition to any other factors that may influence physiological activity of the plant.

Water uptake per unit root length in the zone of maximum sink activity at various harvest dates is summarized in Table 2. Uptake was as high as 0.67 cm^3/cm root/day for roots where water was readily available. Variation in uptake in the zone of maximum sink activity appears to be related to the plant's requirement for water (Table 3) and to root density in the zone of maximum sink activity. Throughout the growth period the plant's demand for water increased as plant weight increased.

Provided that water is readily available, increasing water need by the plant can be met by an increase in

Table 2. Water uptake per unit root length in the zone of maximum sink activity and plant fresh weight and water use at different times after planting.

Plant age*	Water uptake†	Top weight g fresh wt/plant	Water use‡ cm^3/day
24	.09	2.34	31
38	.14	9.66	109
52	.43	31.19	542
59	.43	54.91	929
66	.27	56.85	998
73	.67	143.55	1,400

* Days after planting. † cm^3/cm root/day. ‡ Water use is defined as the volume of water required to maintain the water table.

the total length of absorbing roots or by an increase in the rate of uptake per unit root length, or by both. These data show that increased plant uptake of water was not necessarily associated with increased water uptake per unit length in the region of maximum sink activity. For example, the lower uptake per unit root length in this region at day 66 than at day 59 was associated with the water demand being met by a higher root density. In contrast, at 73 days the plant's increased demands for water were met in part by increased uptake per unit root length with little increase in root density compared with that at day 66. Maximum values of uptake per unit root length agree reasonably well with those suggested by Gardner and Ehlig (6). In the region of maximum uptake, it was difficult to distinguish between the effects of increased water availability, root age, and root resistance on water uptake; however, the high values of uptake per unit length suggest a low root resistance in this region.

Root density profiles are shown in Fig. 7. Root density was expressed on a dry-weight basis and on a length basis. In both cases the most significant feature of the profiles is the bulge observed at the 50- to 70-cm depth. This bulge was first apparent in columns analyzed 52 days after planting. The results indicate that the roots grew rapidly down through the soil until they met the nearly saturated zone above the water table. There they encountered ample water and nutrients for growth; thus, they proliferated in this zone. This large increase in root density, both on a dry-weight basis and on a length basis in the 50- to 80-cm depth, corresponded to the location of the maximum sink term in the latter part of the experiment. The increase in the maximum sink appeared to be partly related to the increase in root density. However, in the remainder of the column there was very little relationship between sink profiles and root density profiles.

A comparison of the sink profiles and the root density profiles indicates that in the presence of a water table, a small portion of the root system can be responsible for the major portion of the water uptake. Summing both sink strength and root length for the 50- to 70-cm depth at 59 days and comparing these data with the sink strength and root length in the whole column showed that about 22% of the root system absorbed about 83% of the water. Similar calculations for the 60- to 80-cm depth at 73 days after planting showed that 23% of the root system was absorbing 94% of the water. Using root density on a dry-weight basis in the same depth increments, 30 and 20% of the root weight absorbed the same proportion of water 59 and 73 days after planting, respectively.

The uptake of water required to meet evapotranspiration demand can be limited by factors in the soil as well as in the plant. It is well known that soil hydraulic conductivity decreases as water content decreases, but few data are available on actual magnitude of its effect on water uptake by plant roots. Results from this experiment clearly show unsaturated hydraulic conductivity as one of the major limiting factors in water uptake by plant roots. The amounts of water absorbed from the upper part of the columns were negligible compared with that absorbed from the capillary fringe. As the plants extracted water, the results of this work suggest that the pressure head difference between the soil and plant roots increased faster than the increase in the hydraulic head gradient could offset the decreasing hydraulic conductivity. Simultaneously, downward root growth becomes important. The net result was that the zone of water uptake, as indicated by the sink strength, was initially near the surface, but moved progressively downward with time. These results are in general agreement with earlier greenhouse studies of Gardner and Ehlig (5) and differ from the water extraction patterns of sorghum (*Sorghum bicolor* (L.) Moench) and warm-season forages grown in the field with surface irrigation (2, 10).

The poor relationship between root density profiles and sink profiles reflects the control the plant can exert on the location of water uptake from soils. Water uptake was not always directly related to root distribution, and the small amount of roots near the capillary fringe absorbed water that was readily available. In this work it was assumed that the energy available for evaporation was constant, and that the total demand for water increased as plant size increased. The increase in the plant's demand for water was met partly by an increase in the uptake per unit length, and partly by an increase in root density where water was readily available.

Thus, for soybeans grown in the presence of a water table, this study indicated that (i) the magnitude of the sink term increased as the plant's demand for water increased, (ii) the hydraulic conductivity was of fundamental importance in determining the magnitude and distribution of the sink term, (iii) there was a poor relationship between the root distribution and sink profiles, and (iv) the increased demand for water by plant tops can be met by an increase in root density in the zone of maximum sink strength or by an increase in uptake per unit root length where water is readily available.

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