Water Uptake by Cotton Root Systems:

An Examination of Assumptions in the Single Root Model ^{1/}Howard M. Taylor and Betty Klepper ^{2/}

MASTER

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^{2/} Soil Scientist, Agricultural Research Service, USDA, and Professor of Soil Management, Iowa State University, Ames, Iowa 50010; Research Scientist, Ecosystems Department, Battelle Northwest Laboratories, Richland, Washington 99352. When the experimental data were collected, both authors were located at Auburn, Alabama. The senior author was employed by ARS-USDA, and the Junior author by the Auburn University Agricultural Experiment Station.

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Water uptake by plant roots can be mathematically described by single root models where the root is assumed to be a line sink of infinite length, uniform radius and uniform absorption properties. Phillip (1957), Gardner (1960) and Cowan (1965) have described movement of water to the root surface from surrounding soil. Under steady conditions, the rate of water uptake per cm of root (q_r , $\text{cm}^3/\text{cm}/\text{day}$) from a soil initially at uniform equilibrium water content has been calculated using the radial flow equation:

$$q_r = \frac{-2\pi k_s [\psi_{\text{root surface}} - \psi_{\text{bulk soil}}]}{\ln \frac{r_{\text{cyl}}}{r_{\text{root}}}} \quad [1]$$

where

k_s is the soil hydraulic conductivity (cm/day),

$\psi_{\text{root surface}}$ is the total water potential at the root surface (cm)

$\psi_{\text{bulk soil}}$ is the total water potential at a distance r_{cyl} =

$r_{\text{bulk soil}}$ (cm)

r_{cyl} is the radius of the cylinder of soil through which water is moving (cm). This is assumed to be 1/2 the distance between adjacent roots. (Gardner, 1960)

r_{root} is the root radius (cm).

Since it is not yet possible to measure water potential at the soil-root surface interface, it is difficult to test single-root models experimentally, especially since root tissue resistances to water transport, while not known precisely, may be significant. If

instead of using the root surface as a boundary, one uses the outer edge of the root xylem, then sink strength can be measured with more certainty, by assigning values of $\psi_{\text{shoot xylem}}$ to equal $\psi_{\text{root xylem}}$. Then an equation, analogous to equation [1], but with different boundaries, can be used to describe water movement into plant xylem from surrounding soil:

$$q_r = \frac{-2\pi k_{\text{sys}} [\psi_{\text{root xylem}} - \psi_{\text{bulk soil}}]}{\ln \frac{r_{\text{cyl}}}{r_{\text{stele}}}} \quad [2]$$

where k_{sys} is the hydraulic conductivity of the combined soil-root radial pathway, $\psi_{\text{root xylem}}$ is a value obtained from shoot water potential measurements, r_{cyl} is as defined in equation [1] and r_{stele} is the radius of the root stele.

This paper describes an experiment conducted at the Auburn rhizotron (Taylor, 1969) for the purpose of determining, under conditions close to those in the field, quantitative information on the parameters in equation [2]. The data were then used to examine three assumptions which have been made in models of root water uptake: (a) that soil resistance to radial water flow is much greater than plant root resistance, (b) that water uptake from a soil layer is proportional to rooting density in that layer, and (c) that the water uptake rate from a soil layer is proportional to the water potential difference between bulk soil and plant root xylem.

Experimental Conditions

Two cotton (*Gossypium hirsutum* L. 'Auburn 623b') plants were grown in a glass-fronted rhizotron compartment that measured 60 cm front to rear, 120 cm side to side, and 188 cm deep. The compartment was filled with Cahaba loamy fine sand (86% sand, > 50 μ , 7% silt 50 - 2 μ , and 7% clay < 2 μ). Specific details of the growing conditions are published elsewhere (Taylor and Klepper, 1974, drying treatment).

To maintain an adequate water supply, the soil was irrigated every 3 or 4 days from planting until July 5. After that date, no water was added to the compartment. Drainage from the bottom of the compartment was provided by 0.1 bar suction through porous plates until July 5 when the drain outlets were sealed to prevent further drainage from the compartment. A metal cover was fitted around the plants and over the soil to minimize evaporation from the soil surface and run-in from rainfall. The experiment started on July 7 when the plants were about 35 cm high and terminated September 5 when the plants were 95 cm high.

Rooting Density

The quantity of root material on the vertical glass viewing surface of the rhizotron wall was assumed to be representative of the roots at that depth throughout the compartment. Rooting density (L_v , cm roots/cm³ soil) was inferred from the number of roots (N) that crossed 105-cm transects at 30-cm depth intervals using a published relationship (Taylor and Klepper, 1974): $L_v = 0.02425 + 0.08129N - 0.0001658N^2$. Rooting density as a function of depth and time is

presented in Table 1. Previous experiments (Taylor et al., 1970, Taylor and Klepper, 1974; private communication, F. M. Melhuish, CSIRO, Irrigation Division, Griffith, N.S.W.), have shown that the standard error of these rooting density values is about 30%. Further, any errors in the L_v values reported here are random, i.e. are not functions of time, water content, or depth.

Rooting density increased with time until the water content of a particular layer decreased to about $0.07 \text{ cm}^3/\text{cm}^3$. Below that water content, rooting density decreased with time until the end of the experiment. After August 18, rooting density decreased at all depths regardless of water content, probably because the cotton plants were maturing.

Soil Water Content

Soil water content was determined as a function of depth and time, and calculations based on the soil water remaining in the profile on various dates were used to determine water uptake rates as well as hydraulic properties of the several soil layers over the growing season.

Soil water contents were measured with a neutron meter calibrated in situ for Cahaba soil. The access tube was installed vertically in the center of the compartment midway between the two plants. Beginning at the 30-cm depth, water contents were measured at 30-cm depth increments between 0700 and 0900 hours at two- or three-day intervals. At each of the six depths measured, water content was plotted as a function of time and graphically smoothed. Smoothed values (Table 2) are used in all subsequent calculations and are assumed to be representative of a 30-cm increment centered at the reported depth.

Calculations of Water Extraction by Roots

Water extraction by roots from a particular depth increment during a specific time period was calculated by the following procedure: The change in water content was determined from successive values in Table 2. Water that flowed into the specific layer during the time was added to this value and water that flowed from the layer was subtracted. Water movement into or out of a depth increment was calculated using the one-dimensional soil water flow equation (equation 4.5, Billel, 1971) with its usual assumptions (Wlute, 1973). For these calculations, average hydraulic conductivity (k , cm/day) was determined from the average water content (θ) of the two depths at two times using a published K - θ relationship (Taylor and Klepper, 1973, Fig. 2). The hydraulic potential (H) was determined by summing a gravitational potential with a pressure potential, determined from the water content-pressure potential relationship for this soil (Taylor and Klepper, 1973, Fig. 1). For this latter water content value, initial and final water contents were averaged for a particular depth. Hydraulic potential gradients were then calculated from successive hydraulic potentials divided by a path length of 30 cm.

Because of possible errors in determining, at high water contents, pressure potential and hydraulic conductivity from neutron meter data, all water content data were excluded from subsequent calculations if the calculated flow between soil layers was as much as one-half the change in stored water. Excluded time periods and depths are enclosed in a dashed line in Table 2. This procedure eliminated from further

consideration values for root system water extraction where errors in calculated water flow might have been large.

Calculations indicated that 0.04, 0.01, 0.01 and 0.01 cm of drainage occurred from the 30-cm depth during the July 14-17, 17-19, 19-21, and 21-24 periods, respectively. For the 60-cm depth, calculated inflow equaled outflow during each time period; but, for the 90-cm depth, a net inflow of 0.03, 0.01, 0.01 and 0.01 cm occurred from the 60-cm depth during the July 14-17, 17-19, 19-21, and 21-24 periods, respectively. The 120-cm depth lost 0.04 and 0.01 cm to the 90-cm depth during the July 19-21 and 21-24 periods, respectively. These values were subtracted or added to the change in stored water to obtain root system water extraction for that depth.

Water uptake per cm of root per day (q_r , $\text{cm}^3/\text{cm}/\text{day}$) was calculated for each soil depth and time period by dividing water withdrawal ($\Delta \theta_r \frac{\text{cm}^3}{\text{cm}^3}$) by rooting density (L_r , cm/cm^3) and the time in days.

$$q_r = \frac{\Delta \theta_r}{L_r \Delta t} \quad [3]$$

Consider the 60-cm depth August 18-21. Each cubic centimeter of soil at that depth lost 0.003 cm^3 water during the 3-day period (Table 2). There was an average of $1.06 \text{ cm roots}/\text{cm}^3$ soil (Table 1). Therefore,

$$q_r = \frac{3.0 \times 10^{-3} \text{ cm}^3}{(1.06 \text{ cm})(3 \text{ day})} = 9.4 \times 10^{-4} \text{ cm}^3/\text{cm}/\text{day at } 0.054 \bar{\theta} \left(\frac{\text{cm}^3}{\text{cm}^3} \right)$$

Increases in q_r appear to be linearly related to increases in soil water content greater than about $0.03 \text{ cm}^3/\text{cm}^3$ water content

(Figure 1). There was no significant ($p = 0.05$) soil depth effect on the $q_r - 0$ relationship. However, one datum point (see arrow, Figure 1) was substantially above the general trend line. This point was obtained during the August 18-21 period at the 180-cm depth when most of the profile contained about $0.05 \text{ cm}^3/\text{cm}^3$ water content. Plant water potential decreased rapidly during this time period and caused a substantially increased potential difference at a time when soil hydraulic conductivity still was sufficient to allow substantial water extraction from that soil layer.

Plant Water Potentials

Continuous traces of stem diameter (Figure 2) were obtained using linear variable differential transformers (Klepper et al., 1971) located on each plant about 25 cm above the ground surface. On 3 days each week, instantaneous plant pressure potentials (ψ_A, ψ_B , cm of H_2O) were determined at times A and B, respectively (Figure 2), using a pressure chamber (Klepper and Ceccato, 1969). Stem diameters, d_A and d_B , were determined from digital voltmeter readings at the same time that ψ_A and ψ_B , respectively, were measured. Values of $\psi_A, \psi_B, d_A - d_B$ and area ACBA (Figure 2) are listed in Table 3 for each plant on several dates. The change in ψ was assumed to be linearly related to the change in d with no hysteresis for the purpose of making the following calculations.

Average plant water potentials ($\bar{\psi}_p$, cm) were calculated as follows

$$\bar{\psi}_p = -6.3 \times 10^3 - \left[\frac{-6.3 \times 10^3 + 19.0 \times 10^3}{1.95 \times 10^{-2}} \right] \left[\frac{1.43 \times 10^{-1}}{24} \right] \text{ cm}$$

$$\bar{\psi}_p = -6.3 \times 10^3 - 3.9 \times 10^3 \text{ cm} = -10.2 \times 10^3 \text{ cm.}$$

The calculated water potentials, $\bar{\psi}_p$, were plotted as functions of time (Figure 3) and graphically averaged for the 2 plants. Values from this smoothed trend line were used in all subsequent calculations.

Hydraulic conductivity of the soil-root system (k_{sys} , cm/day) was calculated using equation [2] with three modifications

- (a) $\psi_{\text{root xylem}}$ was replaced by the average $\bar{\psi}_p$ for the time period.
- (b) r_{cyl} , the outer radius of flow was calculated, after Barley (1971), using Ogston's (1958) theory that the half distance between randomly dispersed segments of roots is given by $d = (4L_v)^{-1/2}$. Example: 60 cm depth, August 18-21,

$$d(\text{cm}) = (4 \times 1.06 \frac{\text{cm}}{3})^{-1/2} = 0.49 \text{ cm.}$$

(c) r_{stole} , the inner radius of flow, was considered to be 2/3 of the root radius, i.e. 0.017 cm in these calculations. We have assumed that the root radius is 0.025 cm (Huck, et al., 1970) and that xylem material extends 2/3 of the distance from the root center to the epidermis.

Thus

$$k_{\text{sys}} = \frac{q_r \ln \frac{(4 L_v)^{-1/2}}{0.017}}{-2\pi (\psi_p - \psi_{\text{bulk soil}})} \quad [5]$$

Soil-root hydraulic conductivity was calculated for all depths and time periods not excluded by the dashed lines of Table 2. An example of calculations is as follows for the August 18-21 time period at the 180-cm depth

$$q_r = 4.7 \times 10^{-3} \text{ cm}^3/\text{cm}/\text{day}$$

$$\psi_{\text{xyl}} = \frac{-12.3 - 13.6 - 15.3}{3} (10^3 \text{ cm}) = -13.7 \times 10^3 \text{ cm}$$

$$\psi_{\text{soil}} = \frac{.083 \frac{\text{cm}^3}{\text{cm}} + .045 \frac{\text{cm}^3}{\text{cm}}}{2} \text{ then using } \psi - \theta \text{ curve} = -0.5 \times 10^3 \text{ cm}$$

$$r_{\text{cyl}} = [4(2.70)]^{-1/2} = 0.30 \text{ cm}$$

$$r_{\text{root}} = 0.017 \text{ cm}$$

$$k_{\text{sys}} = \frac{4.7 \times 10^{-3} \text{ cm}^3/\text{cm}/\text{day}}{2\pi \left[\frac{-13.7 \times 10^3 \text{ cm} + 0.5 \times 10^3 \text{ cm}}{\ln \frac{0.30 \text{ cm}}{0.017 \text{ cm}}} \right]}$$

$$k_{\text{sys}} = 1.6 \times 10^{-7} \text{ cm/day at } \bar{\theta} \text{ of } 0.064 \frac{\text{cm}^3}{\text{cm}^3}$$

Comparison of k_s and k_{sys}

Soil-root system conductivity (k_{sys} , cm/day) decreased with water content (Figure 4) but at a rate that differed greatly from the decrease in hydraulic conductivity of bulk soil. At a water content of 0.18 cm^3/cm^3 , there was a difference of 10^6 cm/day in the 2 conductivities. This difference decreased with water content until it disappeared at a water content of 0.04 cm^3/cm^3 . There appeared to be no effect of soil depth on the relationship between soil-root system conductivity and soil water content.

Data in Figure 4 indicate that the conductivity of a soil-cotton root system is on the order of 10^{-6} cm/day at high soil water potentials. It appears that some resistance associated with the plant root itself or with the rhizosphere (the layer of soil immediately around the root) causes the two curves to be different. It is true that the single root models of Gardner (1960) or Cowan (1965) suggest that a major resistance is located in the rhizosphere but Newman (1969a, b) has disputed this contention, claiming that Gardner (1960) used water uptake rates that were greater than usual field values and that Cowan's values for rooting density were much lower than usual field values. Our data on rooting density (Table 1) and water uptake rate per cm of root (Figure 1) support Newman's (1969a) contention.

With regard to the controversy about the location of the major resistance, our data can be interpreted as follows: The single root

model indicates that rhizosphere resistance increases as soil water content (or soil water potential) decreases. The present data show that the greatest difference between hydraulic conductivities of bulk soil and of the soil-plant root system occurs at the highest water contents. Therefore, the major resistance appears to be located within the root. However, rhizosphere resistance may be associated with decreases in soil-root system conductivity at low water content, especially below $0.07 \text{ cm}^3/\text{cm}^3$.

Root Tissue Conductivities

Soil-root hydraulic conductivity is of the order of 10^{-6} cm/day for these cotton roots. Previous measurements for roots of transpiring plants in solution culture indicate that values of this order of magnitude may be realistic for root tissue. For example, data from Lawlor (1973) and from Hansen (1974) can be used to calculate hydraulic conductivities of $5.6 \times 10^{-6} \text{ cm/day}$ and $4 \times 10^{-6} \text{ cm/day}$, respectively, for wheat roots. For osmotic water movement into detached corn root tips, data of Klepper (1967) can be used to calculate a hydraulic conductivity of $0.4 \times 10^{-6} \text{ cm/day}$. Thus if the resistance implied by k_{sys} in wet soil were assigned to root tissues alone, values would not be very different from experimental values obtained on root tissues growing in solution culture.

These similarities in tissue conductivities may be due to a combination of fortunate circumstances or may be real. It is difficult to compare the two root populations. In the soil, root populations are a heterogeneous mixture of sizes and ages. Our values for root

conductivities and root resistances have been averaged over old and young roots located near the soil surface and deep within the profile. Some of the high resistance could be caused by suberization, but much of it may be the result of structures, especially the endodermis, encountered by water traversing young roots.

The root conductivity values have been calculated using many assumptions. Obviously, estimates of rooting density and of water extraction are subject to experimental error. We believe that the uncertainties in the measurements, however, still allow us to calculate derived parameters to the correct order of magnitude. The assumption has been made that rhizosphere resistance is negligible at $0.18 \text{ cm}^3 / \text{cm}^3$ water content and at the water extraction rates occurring in these experiments. The error introduced by this assumption probably would be progressively greater at lower and lower water content.

The "B" Term of Gardner

Gardner (1964) used a constant, B, to account for rooting activity and geometry. Yang and DeJong (1971) and Allmaras, Black and Rickman (1973) provided evidence that this B term might not be a constant. B can be calculated with the equation (Gardner, 1964)

$$Q = -Bh \sum_{i=1}^n k_{v,i} L_{v,i} (\bar{\psi}_p - \bar{\psi}_{s,i} - \bar{\psi}_{g,i}) \quad [6]$$

where Q is the rate of uptake of water from an area of soil ($\text{cm}^3 / \text{cm}^3 / \text{day}$) with a thickness h(cm). The i subscript denotes the ith layer. Subscripts p, s, and g represent plant, soil matric and soil gravitational potentials respectively. Data reported in the present paper

were used to calculate D using both k_{soil} and k_{sys} for the k term. As soil water content was reduced from 0.168 to 0.04 cm^3/cm^3 , B increased by 5 orders of magnitude when k_{soil} was used but remained approximately constant at 2.0 when k_{sys} was used (Figure 5). This apparent constant did not vary with water content or with soil depth. Therefore, Gardner's assumption that rooting activity is constant appeared valid provided that hydraulic conductivity of the combined soil-root system is used in the calculations rather than hydraulic conductivity of the bulk soil.

Equations 1 and 2 were both derived using the assumption that the major resistance to water extraction by a root segment was located in the soil and values of k_{sys} presented here were calculated using path lengths arising from that assumption. We hesitate to use k_{sys} in modeling water uptake because of this questionable path length assumption. Instead, we have chosen to recalculate water uptake rates in order to account for the potential difference causing flow. We used the formula

$$q_r' = \frac{q_r}{\bar{\psi}_p - \psi_{\text{bulk soil}}} \quad [7]$$

where q_r' is $\text{cm}^3 \text{H}_2\text{O}/\text{cm root}/\text{cm } \Delta\psi/\text{day}$.

This q_r' value linearly decreased with soil water content and was not affected by depth within the profile (Figure 6). The anomalously high data point of Figure 4, which we believe was high because of low plant water potential, is now on the general trend line. The equation describing the relationship between water uptake rate and

soil water content (Figure 6) is

$$q_r' = 10^{-7} (72.44 \theta - 2.459) \quad [8]$$

$$r^2 = 0.87$$

This equation was used to calculate the water remaining in the various soil layers over time in order to compare values predicted by the equation with measured values. The following formula was used for each time increment.

$$\theta_{\text{final}} = \theta_{\text{initial}} + (10^{-7}) (73.44 \theta - 2.459) (L_v) (\bar{\psi}_p - \psi_s) (\text{days}) [9]$$

For example, consider the period from 7 am, August 7 to 7 am, August 9.

At 7 am, August 7

$$\theta = 0.140 \frac{\text{cm}^3}{\text{cm}^3} \text{ (Table 1)}$$

$$L_v = 1.93 \frac{\text{cm}^3}{\text{cm}^3} \text{ (Table 2)}$$

$$\psi_p = -7.2 \times 10^3 \text{ cm (Figure 2)}$$

$$\psi_s = -0.3 \times 10^3 \text{ cm at } \theta = 0.140 \frac{\text{cm}^3}{\text{cm}^3} \text{ (Figure 1, Klepper and Taylor, 1973)}$$

$$\theta_{\text{Aug 8}} = 0.140 - (10^{-7}) [73.44 (0.140) - 2.459] [1.93] [-7.2 \times 10^3 + 0.3 \times 10^3]$$

$$\theta_{\text{Aug 8}} = 0.140 - 0.010 = 0.130 \frac{\text{cm}^3}{\text{cm}^3}$$

$$\theta_{\text{Aug 9}} = 0.130 - (10^{-7}) [73.44 (0.130) - 2.459] [1.93] [-7.2 \times 10^3 + 0.3 \times 10^3]$$

$$\theta_{\text{Aug 9}} = 0.130 - 0.009 = 0.121 \frac{\text{cm}^3}{\text{cm}^3}$$

Using equation 9 we calculated soil water contents as functions of time at each soil depth. Water contents predicted from equation 9 are compared with measured water contents in Figure 7. The close correspondence of predicted and measured water contents indicates that the equation describes water uptake accurately and indicates that water uptake is directly proportional to rooting density and to the water potential difference between plant xylem and bulk soil. Of course, the equation could contain internally compensating errors. However, we believe that such errors would not compensate over the 28 day period and over the range of soil water and root density conditions experienced.

Data in Figure 6 also show that roots at all depths are equally effective when compared at equivalent soil water contents and plant water potentials. Further, data points were on the same trend line regardless of time in the growing season and there was no break in the curve between times when rooting density was increasing and when it was decreasing. We interpret this fact to mean that average root age did not affect q_r because we believe that average root age is greater when root density is decreasing than when it is increasing. Finally, our data indicate that longitudinal resistance to water flow within the root xylem is negligible compared to other resistance in the system. If this statement were not true, we would have obtained soil depth effects on q_r . This last indication is important since our claim to be able to use $\bar{\psi}_p$ in place of $\psi_{\text{root xylem}}$ is dependent on the absence of a high longitudinal resistance in root xylem.

We do not claim that equation 9 represents a completed model. After all, we have used a specific data set to develop the constants that are integral parts of the equation and then have shown that the equation describes our data set. However, we believe that any completed model that describes our cotton root uptake data, in addition to the points listed in the previous paragraph, (a) should accept inputs of rooting density as functions of depth and time, (b) should not carry the assumption that rooting density varies with depth in any specific mathematical relationship, (c) should not assume that water potentials in the leaves or stems is equal to that at the root surface, (d) should not assume that radial root resistance to water flow is negligible or is any specific proportion of soil resistance, and (e) should respond to atmospheric demand. In equation 9 atmospheric demand affects the plant water potential and the relationship between q_r and water content.

Summary and Conclusions

In order to examine assumptions used in water uptake models, especially as they apply to field crops with a large rooting volume, an experiment was conducted at the Auburn rhizotron on cotton plants. Measurements were made of stem diameter, early morning and mid-afternoon plant water potential and of rooting density (L_v) soil water content (θ), soil water potential (ψ_s) and soil hydraulic conductivity (k_s , cm/day) at various depths during the growing season. A technique for calculating $\bar{\psi}_p$, the time-averaged xylem water potential, was developed. Estimates were made of water uptake (q_r , $\text{cm}^3/\text{cm root/}$

day), hydraulic conductivity of the soil-root system (k_{sys} , cm/day) and water uptake per cm potential difference q_r' , $\text{cm}^3/\text{cm root}/\text{cm water}/\text{day}$).

There was no effect of depth on q_r , k_{sys} , or q_r' . Both q_r and q_r' were linearly related to θ but the better fit was obtained with q_r' , which accounts for water potential differences across the root. Soil-root conductivity (k_{sys}) was six orders of magnitude less than bulk soil conductivity (k_g) at high θ , indicating that significant resistances to lateral water transport occur in root tissues. When the linear relationship between q_r' and θ were used to calculate water loss from the profile given θ , L_v and $(\bar{\psi}_p - \psi_s)$, values were in close agreement with measured values.

These results indicate that plant resistance to radial water transport is much greater than soil resistance, that water uptake is proportional to rooting density and to the water potential difference between bulk soil and plant xylem.

References

Allmaras, R. R., A. L. Black, and R. W. Rickman. 1973.

Tillage, soil environment and root growth in Conservation Tillage-
The proceedings of a national conference. Publ. by Soil Conserva-
tion Society of America, Ankeny, Iowa.

Barley, K. P. 1971.

Root (Botany). Encyclopedia of Science and Technology. Third
Ed. 1971. McGraw-Hill Book Company. N. Y.

Cowan, I. R. 1965.

Transport of water in the soil-plant-atmosphere system. J.
Appl. Ecol. 2:221-239.

Gardner, W. R. 1960.

Dynamic aspects of water availability to plants. Soil Sci. 89:
63-73.

Gardner, W. R. 1964.

Relation of root distribution to water uptake and availability.
Agron. J. 56:35-41.

Huck, M. G., Betty Klepper, and H. M. Taylor. 1970.

Diurnal variations in root diameter. Plant Physiol. 45:529-530.

Klepper, B., V. D. Browning, and H. M. Taylor. 1971.

Stem diameter in relation to plant water stress. Plant Physiol.
48:683-685.

Hansen, C. K. 1974.

Resistance to water transport in soil and young wheat plants.

Acta Agriculturae Scandinavica 24:37-48.

Hillel, D. 1971.

Soil and water - Physical Principles and Processes. Academic Press, New York.

Klepper, B., and R. D. Ceccato. 1969.

Determinations of leaf and fruit water potential with a pressure chamber. Hort. Res. 9:1-7.

Klepper, Betty. 1967.

Effects of osmotic pressure on exudation from corn roots. Aust. J. Biol. Sci. 20:723-735.

Klute, A. 1973.

Soil water flow theory and its application in field situations. In Field Soil Water Regime ed. Bruce, R. R., K. W. Flach, and H. M. Taylor. Publ. by Soil Science Society of America, Madison, Wisc.

Lawlor, D. W. 1973.

Growth and water absorption of wheat with parts of the roots at different water potentials. New Phytologist 72:297-305.

Newman, E. I. 1969a.

Resistance to water flow in soil and plant. I. Soil resistance in relation to amounts of roots: Theoretical estimates. J. Appl. Ecol. 6:1-12.

Newman, E. I. 1969b.

Resistance to water flow in soil and plant. II. A review of experimental evidence on the rhizosphere resistance. J. Appl. Ecol. 6:261-272.

Ogston, A. G. 1958.

The spaces in a uniform random suspension of fibers. Faraday Soc. Trans. 54:1754-1757.

Phillip, J. R. 1957.

The physical principles of water movement during the irrigation cycle. Int. Cong. Irrig. Drain., Proc. 3rd. 8.125-8.154.

Taylor, H. M. 1969.

The rhizotron at Auburn, Alabama. A plant root observation laboratory. Auburn Univ. Agr. Exp. Sta. Circ. 171. 9 p.

Taylor, H. M., M. G. Huck, B. Klepper, and Z. F. Lund. 1970.

Measurement of soil grown roots in a rhizotron. Agron. J. 62:807-809.

Taylor, H. M., and B. Klepper. 1973.

Rooting density and water extraction patterns for corn. Agron. J. 65:965-968.

Taylor, H. M., and B. Klepper. 1974.

Water relations of cotton. I. Root growth and water use as related to top growth and soil water content. Agron. J. 66: (In Press.).

Yang, S. J., and E. DeJong. 1971.

Effect of soil water potential and bulk density on water uptake patterns and resistance to flow of water in wheat plants. Can. J. Soil Sci. 51:211-220.

Table 1. Rooting densities (L_v cm root/cm³ soil) as functions of depth and time.

		Depth					
		30	60	90	120	150	180
July	7	.97	.27	.24	.16	.07	0
	10	1.07	.45	.45	.24	.13	.10
	12	1.20	.56	.69	.34	.19	.10
	14	1.40	.64	.85	.45	.24	.27
	17	1.47	.77	1.00	.53	.29	.27
	19	1.60	.89	1.13	.61	.37	.43
	21	1.40	.87	1.31	.66	.35	.35
	24	1.77	1.05	1.53	.81	.51	.43
	26	1.77	1.32	1.68	.89	.56	.66
	28	1.77	1.30	1.70	.94	.72	.98
	31	1.77	1.25	1.83	1.09	.85	1.13
	Aug 2	1.82	1.32	1.78	1.09	.87	1.21
	4	1.77	1.42	2.04	1.31	1.20	1.58
Aug	7	1.72	1.35	2.02	1.55	1.80	1.88
	9	1.60	1.15	1.88	1.53	2.05	2.38
	11	1.38	1.05	1.81	1.53	2.00	2.81
	14	1.58	1.20	1.81	1.48	2.12	2.81
	16	1.53	1.15	1.73	1.41	2.02	2.53
	18	1.36	1.10	1.71	1.43	2.11	3.01
	21	1.13	1.02	1.71	1.33	1.58	2.39
	23	.90	.90	1.46	1.23	1.51	2.10
	25	.50	.84	1.38	1.25	1.51	1.81
	27	.61	.77	1.36	.95	1.13	.74
Sept	30	.56	.82	1.08	.87	.97	0
	1	.31	.61	1.08	.87	.69	.10
	5	.28	.50	.85	.36	.09	0

Table 2. Volumetric water contents as functions of depth and time. Entries enclosed by the dashed line were excluded from calculations because of possible errors in calculating flows from one soil layer to another. See text for details.

		Depth					
		30	60	90	120	150	180
		cm^3/cm^3					
July	7	.216	.198	.197	.215	.210	.251
	10	.200	.180	.177	.201	.210	.260
	12	.177	.166	.167	.195	.210	.269
	14	.158	.155	.158	.190	.210	.278
	17	.138	.141	.147	.193	.210	.295
	19	.126	.132	.140	.178	.210	.307
	21	.118	.123	.132	.172	.210	.320
	24	.107	.110	.120	.164	.210	.329
	26	.100	.102	.113	.157	.207	.322
	28	.094	.095	.105	.148	.199	.309
	31	.084	.085	.094	.138	.187	.279
Aug	2	.068	.079	.086	.130	.180	.260
	4	.074	.074	.078	.123	.172	.241
	7	.067	.067	.067	.107	.140	.213
	9	.063	.063	.062	.095	.120	.177
	11	.059	.059	.056	.084	.104	.162
	14	.055	.055	.052	.073	.091	.128
	16	.053	.053	.049	.067	.071	.106
	18	.051	.051	.046	.061	.062	.083
	21	.048	.048	.042	.053	.052	.045
	23	.046	.046	.040	.048	.046	.038
	25	.044	.044	.038	.043	.042	.035
Sept	27	.042	.042	.036	.040	.038	.033
	30	.040	.040	.034	.036	.034	.032
	1	.039	.039	.033	.035	.033	.032
	5	.037	.037	.032	.034	.032	.032

Table 3. Plant pressure potentials, changes in stem diameter, and stem shrinkage areas as outlined in Figure 1.

Date	Plant 1					Plant 2				
		ψ_A	ψ_B	$d_A - d_B$	AREA		ψ_A	ψ_B	$d_A - d_B$	AREA
		10^3 cm	10^3 cm	10^{-1} cm	10^{-1} cm hrs		10^3 cm	10^3 cm	10^{-1} cm	10^{-1} cm hrs
July	10	-2.7	-13.0	0.020	0.13		-2.3	-	0.012	0.09
	12	-3.0	-11.0	0.019	0.11		-3.0	-11.0	0.010	0.06
	14	-2.7	-9.0	0.043	0.14		-2.3	-	-	-
	17	-2.0	-12.7	0.081	0.57		-3.0	-12.0	0.066	0.38
	19	-3.7	-11.7	0.080	0.62		-3.3	-11.7	-	-
	21	-3.0	-12.0	0.067	0.60		-4.3	-14.0	0.079	0.69
	24	-2.3	-16.3	0.168	1.19		-2.7	-14.7	0.237	1.82
	26	-1.7	-11.7	0.069	0.37		-2.3	-12.3	0.137	0.79
Aug	28	-1.7	-12.3	0.088	0.90		-1.3	-12.7	-	-
	2	-2.0	-13.7	0.174	1.57		-4.0	-13.3	0.198	2.12
	4	-2.3	-11.7	0.044	0.53		-3.3	-12.3	0.068	0.69
	7	-2.7	-17.7	0.197	1.52		-3.3	-16.0	0.226	1.82
	9	-2.7	-15.3	0.136	1.02		-3.0	-17.3	0.195	1.55
	14	-4.0	-16.7	0.118	0.98		-5.7	-13.3	0.121	0.96
	16	-6.3	-19.0	0.195	1.43		-4.7	-20.3	0.269	2.16
	18	-5.0	-19.0	0.239	2.78		-5.0	-21.7	0.356	2.40
	21	-10.7	-25.3	0.217	2.96		-12.7	-25.3	0.310	4.12
	23	-13.3	-28.7	0.211	2.43		-11.7	-29.3	0.323	3.77
	25	-14.0	-31.3	0.249	3.50		-14.3	-31.0	0.330	4.30

Figure 1. Water uptake per cm of root material as a function of soil water content for various soil depths. The arrow indicates a datum point for the 180-cm depth where water content at that depth was substantially greater than that at lesser depths. (see text for discussion)

Figure 2. Cotton stem diameter as a function of time during a 2-day period in August 1972. Points A and B correspond to times when samples were taken for plant pressure potential measurements and point C is the time when stem diameter returned to the value at point A. The area enclosed by points ACBA was used in calculating plant pressure potential. (see text for further details)

Figure 3. Average plant pressure potential, $\bar{\psi}_p$, of plant 1 (circles) and plant 2 (squares) as a function of time. Values were determined from the hand-drawn dashed line for subsequent calculations where plant pressure potential was required.

Figure 4. A comparison of the hydraulic conductivities of bulk soil (Taylor and Klepper, 1973, Fig. 2) with that of the soil-plant root system at various soil depths and soil water contents.

Figure 5. Value of "B" from the Gardner (1964) equation 4 as calculated using soil hydraulic conductivity (k_s , circles) and soil-plant root hydraulic conductivity (k_{sys} , squares).

Figure 6. The relationship between soil water content of a particular layer and water uptake per cm of root per cm potential difference per day. The arrow indicates the anomalous datum point that was discussed in relation to Figure 1.

Figure 7. A comparison of measured soil water contents (solid lines) with water contents that were calculated using equation [9] (open triangles). The "S" near a measured water content signifies the starting point for the calculated water content at that depth.