WATER UPTAKE BY COTTON ROOTS DURING AN IRRIGATION CYCLE

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Abstract

Two-month-old cotton plants, growing in a rhizotron compartment filled with loamy fine sand surface soil, were subjected to an irrigation cycle. Estimates of rooting density, soil water content, soil water potential, water extraction per unit length of root, plant height, and leaf water potential were made throughout this cycle.

The soil dried progressively from top to bottom. Water extraction per unit length of root was greater in wetter soils and decreased exponentially with soil water potential. In general, deep roots were as effective as shallow roots in water extraction. Rooting intensity was greater in the upper soil at first, but became uniform later. After irrigation, water extraction per unit length of root was about the same at all depths.

I. Introduction

Water uptake by roots has been studied under many soil and climatic conditions. Usually, water content of a moist soil decreases more rapidly in shallow than in deep horizons. As a result, it is sometimes assumed that shallow roots are more effective in water extraction than those deeper in the profile. However, recent reviewers (Gardner 1965; Slatyer 1967) have stated that water extraction from a uniformly moist soil is roughly proportional to the amount of root material present. These reviewers also state that the rate of water uptake usually decreases as the soil dries because hydraulic conductivity decreases with water content.

Much of the data in the literature on water uptake by roots was obtained by determining soil water content on successive dates, ignoring evaporation and drainage. More important, root density was usually measured, if at all, only at termination. Any changes in root density during a drying cycle were ignored. In view of these considerations much of the presently available data is open to alternate interpretations and needs to be re-examined (Newman 1969*a*, 1969*b*), preferably with techniques which permit continuous, non-destructive observation of both rooting parameters and soil water status.

An underground root laboratory or rhizotron (Taylor 1969) provides an opportunity for measuring both root density and water uptake with depth. In the experiments reported here, measurements were made of root density and of water removal from soil in a rhizotron compartment by roots of a mature cotton plant during an irrigation cycle. Objectives of the research were (1) to determine the changes in root density that occur during an irrigation cycle, and (2) to evaluate effectiveness of cotton roots at various depths in extracting water during an irrigation cycle.

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II. Methods and Materials

Two cotton (*Gossypium hirsutum* L. line "Auburn 7-683") plants were grown in one compartment at the Auburn rhizotron where tops were exposed to a field environment while root systems were observed through the transparent acrylic plastic side of an underground compartment. The compartment was 120 cm side-to-side, 188 cm top-to-bottom, and 60 cm front-to-rear.

In February 1970, Cahaba surface soil from a cropped area was sieved, placed in the compartment, and settled by watering. After the soil had drained, the compartment was refilled to the original soil level. Soil test potassium and phosphorus values were high and pH was 6·0. Soil bulk density averaged 1·34 g cm^{-3} (range 1·30–1·38 g cm^{-3}). The Cahaba soil is a river terrace loamy fine sand with 86% sand (>50 μm), 7% silt (50–2 μm), and 7% clay (<2 μm).

On April 24, two groups of seeds were planted 2 cm deep and equidistant between the front and rear walls. Each group was planted about 30 cm from the side wall. About 3 weeks later, the plants were thinned to one at each location. On May 18, the soil was fertilized with the equivalent of 440 kg/ha of both nitrogen as $(NH_4)_2SO_4$ and potassium as KCl.

The soil was watered periodically and the plants were allowed to grow until the root systems had extended to the bottom of the rhizotron compartment. On July 1, the soil was thoroughly watered and a suction of 0·1 bar was applied to porous plates at the bottom of the compartment to drain off excess water. When drainage had slowed to 3 litres per day on July 4, suction was removed and the outlet tubes were clamped. A metal cover was installed 6 cm above ground level to exclude rainfall and to reduce evaporation from the soil surface. The cover was complete except for an area about 30 cm^2 around each plant.

Soil water content was determined periodically at 15-cm depth increments using the thermal neutron method calibrated for a rhizotron compartment filled with Cahaba soil. Location of the access tube was the same during calibration and measurement. The values reported for a given depth refer to a layer centred at that depth. Immediately after irrigation, the value at 180 cm had to be omitted because of water in the bottom of the access tube. Soil water potential was determined daily at 8 a.m. between July 7 and August 2 at 30-cm depth increments beginning at 23 cm, with commercially available ceramic-covered thermocouple psychrometers (Wiebe *et al.* 1970) individually calibrated (E. L. Fiscus and M. G. Huck, personal communication) for determining water potential at the ambient temperature.

Plant height was measured daily at 8 a.m. from July 1 to August 3. Leaf area was measured July 2 and August 3 by a length–width method (Ashley, Doss, and Bennett 1963). Plant water potential at 8 a.m. was determined with a pressure chamber (Klepper and Ceccato 1969). The line transect method (Taylor *et al.* 1970) was used to estimate root intensity (centimetres of root per 1 cm^2 viewing area) three times a week between July 1 and July 27, and daily between July 27 and August 3. Data on root density were obtained by assuming that all roots within 2 mm of the plastic–soil interface were visible and that those farther away were not visible.

To check for possible root concentration at the wall, four soil samples 10 by 10 cm along the wall and 2·5 cm thick were collected on August 3 from the soil–plastic and soil–rear wall interfaces at 30-, 60-, 90-, 120-, and 150-cm depths. Six cores 5·2 cm in diameter and 6 cm long were also collected from bulk soil at each depth. Thus, there were 14 samples from each depth. Soil from these samples was washed through a 60-mesh screen (0·25-mm openings). The roots were rewashed, dried at 65°C, and weighed. Soil–water hydraulic conductivity was calculated from data obtained with the one-step method (Doering 1965) on soil cores collected from the compartment after the irrigation cycle was completed.

III. Results and Discussion

(a) *Plant Shoot Measurements*

The shoots grew 17 cm in the first 10 days after irrigation (July 1–10), 12 cm in the second 10 days, and then almost ceased to grow. The first blooms appeared on July 1. Plants were then 82 cm high and on July 24, 112 cm high. Total leaf area of the two plants increased from 2·6 m^2 on July 2 to 5·3 m^2 on August 3. Leaf water potential at 8 a.m. ranged between −3 and −5 bars, depending upon the aerial environment of a particular morning, until July 26, when it showed a marked drop to −10 bars. On July 27, it was −15 bars. On July 28, after irrigation had begun on the previous day, the plant water potential at 8 a.m. returned to the −3 to −5 bar range.

(*b*) *Soil Water Measurements*

After the soil had been irrigated on July 1 and drained for several days, the water content (cm^3/cm^3) in the profile ranged from about 7% at the 30-cm depth to 23% at the 165-cm depth (Table 1). Throughout the drying period water content decreased

TABLE 1

MEAN VOLUMETRIC SOIL WATER CONTENTS DURING AN IRRIGATION CYCLE

The neutron source was centred at the depths shown

Depth of Neutron Source (cm)	Mean Volumetric Soil Water Content (cm^3/cm^3)								
	July 7	July 13	July 15	July 17	July 21	July 24	July 27	July 31	August 3
30	0·073	0·045	0·037	0·035	0·033	0·031	0·031	0·216	0·167
45	0·105	0·040	0·039	0·037	0·034	0·033	0·033	0·223	0·181
60	0·110	0·049	0·039	0·037	0·035	0·033	0·033	0·225	0·184
75	0·102	0·049	0·042	0·040	0·037	0·035	0·031	0·223	0·181
90	0·102	0·055	0·043	0·040	0·036	0·034	0·032	0·227	0·183
105	0·107	0·066	0·049	0·045	0·037	0·035	0·033	0·226	0·189
120	0·122	0·084	0·062	0·049	0·038	0·036	0·034	0·228	0·193
135	0·144	0·100	0·091	0·067	0·041	0·039	0·034	0·241	0·197
150	0·177	0·161	0·132	0·100	0·047	0·041	0·037	0·251	0·205
165	0·231	0·195	0·166	0·139	0·054	0·049	0·039	0·267	0·215
180	—	0·238	0·202	0·175	0·072	0·064	0·039	0·259	0·221

at each depth until July 27 when there was a uniform water content of about 3% throughout the profile. On that day the soil was irrigated, and suction was applied for

TABLE 2

SOIL WATER POTENTIAL AT 8 a.m. AT SEVERAL DEPTHS DURING AN IRRIGATION CYCLE

The thermocouple psychrometers were calibrated for potential determination at the ambient temperature

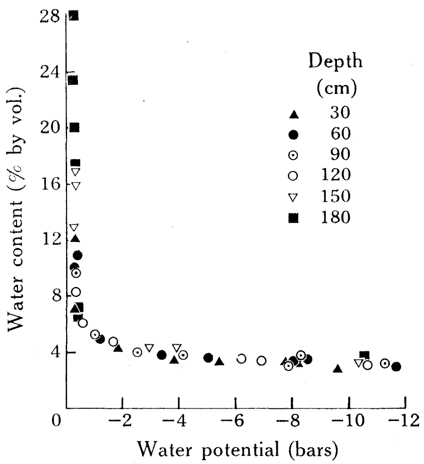
Depth (cm)	Soil Water Potential (bars)							
	July 7	July 13	July 15	July 17	July 21	July 24	July 27	Aug. 3
23	−0·3	−1·8	−3·8	−5·5	−8·2	−7·6	−9·0	−0·6
53	−0·4	−1·4	−3·7	−5·4	−8·2	−8·6	−11·7	−0·6
83	−0·3	−0·8	−2·2	−3·8	−7·6	−8·2	−11·0	−0·5
113	−0·3	−0·2	−0·7	−2·2	−7·0	−7·6	−11·0	−0·7
143	−0·3	−0·2	−0·2	−0·3	−3·1	−4·1	−8·4	−0·1
173	−0·4	−0·4	−0·3	−0·2	−0·3	−0·4	−10·3	−0·1

4 days to the porous drainage plates. Considering both the amount of water applied and that removed by suction, the soil was irrigated with 55 cm of water. By July 31,

when drainage had nearly ceased, the water content in the profile was about 23% and tended to increase with depth. Between July 31 and August 3, the water extracted from each depth increment was uniform throughout the profile; it varied from 3 to 5% at a given depth and showed no trend with depth.

On July 7 soil water potential was −0·3 to −0·4 bars at all depths (Table 2). By July 21, when shoot growth ceased, soil potential was −8·2 bars at the 23- and 53-cm depths, but was −0·3 bars at the 173-cm depth. Immediately prior to irrigation on July 27, potential at every depth was less than −8·4 bars.

Fig. 1



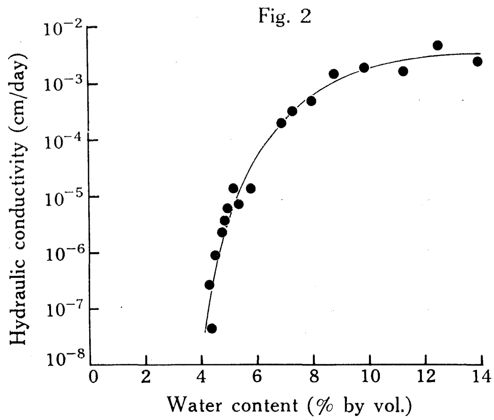


Fig. 1.—Water content as determined with a neutron meter as a function of *in situ* soil water potential at 8 a.m. as determined with a thermocouple psychrometer.

Fig. 2.—Hydraulic conductivity as a function of volumetric water content for the Cahaba soil.

Figure 1 shows the relationship between soil water content and water potential at six depths. Values from all depths fall on the same curve. Therefore, overburden pressure (Rose 1966) apparently was unimportant in this experiment. A water content–matrix potential curve obtained by desorption in a pressure plate apparatus was almost identical with the *in situ* relation between water content as determined with the neutron meter, and water potential as obtained with the thermocouple–psychrometer network (Fig. 1). This data check assured that the psychrometer calibrations were reasonably accurate and that soil osmotic potential was negligible.

Hydraulic conductivity of this sandy soil material was about 5×10^{-3} cm day^{-1} at a volumetric water content of 8%, but decreased to 1×10^{-6} cm day^{-1} at a water content of 5% (Fig. 2). Calculations show that upward movement of water from wetter to drier layers was unimportant during most of the drying phase of this irrigation cycle. As an example, consider the 83- and 113-cm depths between July 13 and 15. The upward potential gradient was approximately 1 bar (Table 2) at an average water content of about 5% (Table 1). Hydraulic conductivity at this water content was about 1×10^{-6} cm day^{-1} (Fig. 2). Upward movement of water through a plane at 90 cm would be 7×10^{-5} cm during the 2-day period. During the same period, water content was reduced from 6 to 4·5%. Thus, upward movement of water through the soil could have caused an error of the order of 1% in estimating root water uptake during this period.

(c) *Root Distribution*

The pattern of root intensity (centimetres of root per 1 cm^2 of viewing area) shifted during the irrigation cycle (Table 3). Early in the drying phase there were more

Table 3

ROOT INTENSITY AT SEVERAL DATES DURING AN IRRIGATION CYCLE

15-cm Depth Increments Centred at Depths (cm) of:	Root Intensity (cm roots/1 cm^2 viewing area)								
	July 7	July 13	July 15	July 17	July 21	July 24	July 27	July 31	August 3
15	0·28	0·19	0·19	0·12	0·14	0·22	0·05	0·23	0·24
30	0·31	0·22	0·19	0·12	0·18	0·16	0·13	0·18	0·19
45	0·26	0·12	0·16	0·07	0·10	0·13	0·09	0·04	0·09
60	0·22	0·17	0·23	0·09	0·16	0·12	0·22	0·15	0·16
75	0·08	0·02	0·13	0·02	0·05	0·07	0·10	0·17	0·15
90	0·07	0·05	0·16	0·05	0·11	0·15	0·16	0·18	0·19
105	0·10	0·03	0·15	0·04	0·07	0·15	0·12	0·17	0·17
120	0·08	0·02	0·13	0·03	0·06	0·04	0·18	0·12	0·18
135	0·04	0·03	0·19	0·12	0·08	0·12	0·26	0·16	0·18
150	0·11	0·07	0·18	0·10	0·11	0·10	0·24	0·18	0·19
165	0·03	0·07	0·22	0·05	0·16	0·05	0·25	0·17	0·20
180	0·01	0·02	0·19	0·15	0·20	0·11	0·29	0·22	0·25

roots in the upper three layers than in the rest of the profile. When most of the water had been extracted, roots were more concentrated in the bottom three layers. After irrigation (July 27) new roots appeared, especially in the upper two layers.

Table 4

ROOT MATERIAL SAMPLED AT VARIOUS LOCATIONS 7 DAYS AFTER REWATERING

Depth (cm)	Root Dry Weight (g/250 cm^3 of soil)		
	Plastic Wall	Compartment Centre	Rear Wall
30	0·0249	0·0124	0·0380
60	0·0246	0·0268	0·0220
90	0·0169	0·0125	0·0169
120	0·0208	0·0176	0·0394
150	0·0436	0·0204	0·0325

At this point, the question arises whether the root distribution in bulk soil can be determined from root intensity values at the viewing surface. Answers to this question were obtained in three ways. First, root dry weights from soil samples oriented along the viewing area were compared with weights from bulk soil (Table 4). At some depths root weights were greater at the viewing area than in bulk soil. This root weight concentration effect ranged from none to about twofold, but averaged about 1·3–1·5.

Second, visual examinations at the time of sampling for root weights showed few, if any, additional roots near the viewing surface and root morphology was the same. Third, probable root densities in the bulk soil were calculated from root dry weight data by assuming that the roots were 95% water and were 0·04 cm in diameter. These root densities were slightly lower than those obtained by multiplying root intensities by five on the assumption that roots within 2 mm of the viewing surface were counted. The value obtained from root intensity was of the order of 1·2 times this calculated value. These three checks showed that any concentrating effect of the plastic wall probably did not cause errors greater than 30–50% in the root density data. In any event, any errors in root density were systematic and did not affect the validity of conclusions relating to the specific objectives of this research.

(*d*) *Water Extraction by Roots*

Water extraction (cm^3) per unit length of root per day was fairly uniform early in the drying cycle but gradually became proportionately less in the upper (dry) layers and greater in the lower layers (Table 5). From July 21 to July 27 there was little water

TABLE 5

WATER EXTRACTION BY COTTON ROOTS DURING SEVERAL INTERVALS OF AN IRRIGATION CYCLE

These values are not corrected for any possible root-concentrating effects of the plastic–soil interface

15-cm Depth Increment Centred at Depths (cm) of:	$10^{-2}\times$ Volume of Water Extracted (cm^3/ 1 cm root/ day) for Following Periods:						
	July 7–13	July 13–15	July 15–17	July 17–21	July 21–24	July 24–27	July 31–August 3
30	0·4	0·4	0·1	0·1	0·06	0·03	1·7
45	1·2	0·1	0·2	0·2	0·04	0·04	3·3
60	1·1	0·6	0·1	0·1	0·07	0·03	1·7
75	3·4	1·1	0·3	0·4	0·23	0·33	2·0
90	2·6	1·2	0·3	0·3	0·11	0·09	1·6
105	2·2	2·0	0·4	0·8	0·09	0·10	1·5
120	2·7	3·0	1·7	1·2	0·26	0·12	1·7
135	4·2	0·9	1·5	1·3	0·18	0·22	1·6
150	0·7	2·5	2·4	2·7	0·35	0·27	1·6
165	2·8	2·2	2·1	4·0	0·33	0·42	1·7
180	—	3·1	1·7	3·1	0·35	0·86	1·0

extraction in any layer. After irrigation, water extraction per unit length of root increased markedly and was again fairly uniform throughout the profile. Presumably, in the upper two layers the high permeability of the new root tissue counteracted any additional resistance of the older, suberized roots.

Water uptake per unit length of root per day was exponentially related to soil water potential at all depths and, for a given depth, water uptake decreased as bulk soil water potential decreased (Fig. 3). This phenomenon was expected because soil conductivity decreases with water potential.

The extraction data were collected over periods of 2 or more days where there were both long-term and diurnal variations in plant water potential, soil water potential, and soil water conductivity. Additionally, root–soil contact (Huck, Klepper, and Taylor 1970) and plant resistances to water flow (Kramer 1969) varied. These uncertainties preclude using these data to estimate any instantaneous parameters such as rhizosphere resistance or root surface water potential.

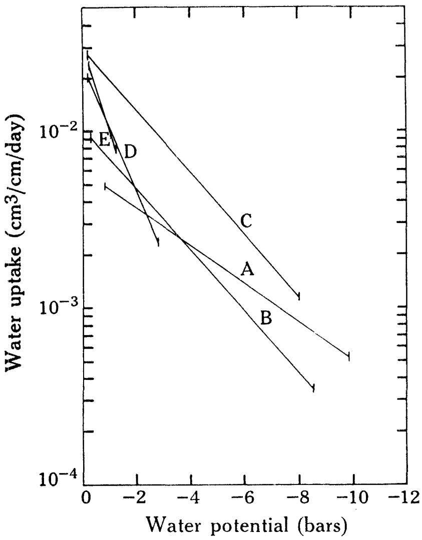


Fig. 3.—Water uptake as a function of soil water potential at 8 a.m. as measured by a thermocouple psychrometer. Profile depths and correlation coefficients are: *A*, 30 cm, −0·934; *B*, 60 cm, −0·961; *C*, 120 cm, −0·996; *D*, 150 cm, −0·855; *E*, 180 cm, −0·476.

Regardless of the possible errors inherent in drying cycle experiments, our data showed that (1) the root density profile changed substantially during an irrigation cycle, and (2) deep roots were at least as effective as shallow roots in water extraction.

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