Soil Water Availability and Water Use Efficiency

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Abstract

The rate of soil water extraction by roots depends on the momentary atmospheric conditions and soil water availability, which in turn depends on the resistance to water flow from the soil bulk to the soil-root interface, and water flow across the root tissues and into the root xylem. Moisture depletion in the rhizosphere induces water flow from the surrounding soil volume to replenish the depleted water. The hypothesis in the current lecture is that the dynamic rather than the static features of the soil water in the effective root zone should be considered when one examines water availability to the plant roots and irrigation scheduling. Irrigation scheduling is designed by using different soil parameters (porosity, density, saturated hydraulic conductivity, etc.). When water availability is included in the design, the retention curve of the given soil is used as well. Since this curve is intrinsically based on soil water statics and provides information on the water amount at different suctions, it represents the potential rather than the actual water availability to the plant. Water flux from the soil bulk to the plant root depends on the momentary value of the hydraulic conductivity within the soil volume that encircles the roots and on the hydraulic head gradient between this soil volume and the outer surface of the root. The momentary balance between the actual water flux from the soil volume surrounding the root and the potential water extraction rate (which depends mainly on the momentary atmospheric conditions) determines whether soil moisture is fully available to the plant. By "fully available" we mean that the water extracted from the vicinity of the root can be fully replenished in a matter of moments. When the root rhizosphere cannot be immediately replenished, water uptake by the root will be limited by the transport ability of soil water toward the roots, i.e. by the conductivity of the rhizospheric soil. Results of field and greenhouse experimental studies, which verify the hypothesis, will be introduced. Irrigation scheduling based on the dynamic water availability concept increases water use efficiency, which is vital for areas where water is scarce, and reduces the deterioration of groundwater quality by agrochemicals transported by excessive irrigation water percolation.

Introduction

Understanding the spatial and temporal variations in water uptake by roots between consecutive irrigations is of fundamental importance for optimal irrigation design and management to increase water use efficiency and minimize groundwater pollution by water percolation. Studies on this subject have mostly been conducted with potted plants or have made use of modeling approaches and theory that led to the conclusion that in a uniformly well-watered soil profile, root distribution can be considered to be the dominant factor in determining water uptake pattern (Molz, 1981; Passioura, 1988; Campbell, 1991). A few reports have also suggested that in a uniformly well-watered soil profile, shallow roots tend to be more effective in water uptake than deeper roots (Klepper, 1990; Gardner, 1991; Green and Clothier, 1995). During a drying cycle, the

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upper soil layers become dry and the water uptake shifts downwards, where availability of soil water is higher: this has been referred to by Gardner (1991) as the "moving sink". The increase in absolute water uptake rate by the roots in the deeper soil layers with drying of the soil profile has been attributed to an increasing driving force for water transport caused by lowered root water potential (Klepper, 1990). Modeling results of Reid and Huck (1990) indicated that the water potential distribution in the soil profile significantly affects the extraction pattern. On the other hand, indirect evidence suggests that the downward shift of root activity may be caused by the decreasing physical contact at the soil-root interface in the drying upper soil layers (Herkelrath et al., 1977; Bristow et al., 1984). This concept provides a satisfactory explanation for the increased resistance to water flow as soil dries when the theory suggests that soil resistance is still negligible (Herkerlrath et al., 1977; Molz, 1981; Bristow et al., 1984).

The current study was designed to improve our understanding of the spatial and temporal evolution of root water uptake under field conditions. It was hypothesized that the spatial and temporal variations in the root uptake rate are dominated by both the bulk soil resistance, which is the opposite of soil hydraulic conductivity and is directly related to the soil moisture content, and the root position relative to the plant base. Proof of this required, first, an in situ measurement of the root system distribution and functionality with high spatial and temporal resolution, a difficult task due to instrumentation limitations. Since root growth after crop pollination usually slows down or even ceases (Mengel and Barber, 1974; Klepper, 1990), it can be considered that the root density is a constant parameter at that stage and that the corresponding water uptake pattern can be treated as a function of changing soil water conditions. Combining the TDR system (Coelho and Or, 1999) and a direct measurement of the sap flow rate (Green and Clothier, 1999) allows accurate measurements of the effectiveness of various fractions of the root system.

Materials and methods

The following presentation will describe the results obtained in two field and one greenhouse studies. Field study No1 was conducted during August and September of 1994 in an 18 years old orchard of Shamouti orange (Citrus sinensis L. Osbeck) on sour orange (Citrus aurantium L.) rootstock at the Faculty of Agriculture's Research Station in Rehovot, Israel. The soil was a Rehovot Sand soil (Rhodoxeralf) with 1 % organic matter content and consisting of 70 % fine sand, 15 % coarse sand, 10 % silt, and 5 % clay. The trees were irrigated twice weekly: a main irrigation of 350 L per tree and a supplementary irrigation of 180 L per tree. The irrigation system consisted of pressure-compensated mini-sprinklers with one emitter per tree and a discharge of 70 L h^{-1}. Field study No2 was also carried out at the Faculty of Agriculture's Research Station in Rehovot, Israel during the summer of 1997 on a 1,000 m^2 plot. Sweet corn seeds were hand-sown to a uniform density of 8 m^{-2}. Row spacing was 0.95 m. An auto-controlled drip irrigation system with a drip line in each row was used. A line source along the dripper pipes was obtained by maintaining a small distance between the drippers (every 25 cm) along the pipe. From sowing to the beginning of silking, plants were kept well-watered and irrigation scheduling started at the beginning of silking. On-line irrigation scheduling was based on the ratio between daily actual vs. potential transpiration: the actual value was determined from sap flow measurement (Cohen et al., 1988) and the potential value calculated from a modified Penman-Monteith equation (Fuchs et al., 1987). A 50% reduction of the ratio from its initial value (after irrigation) triggered the next irrigation. The amount of water applied at each irrigation was 125% of the total actual transpiration in the previous cycle. As a result, the irrigation interval was only 3 days.

An automated TDR system was used in the two field experiments to continuously measure soil moisture content variations with time. The TDR system was comprised of a cable tester (1502B; Tektronix, Beaverton, OR) interfaced to a Campbell Scientific CR10 data logger equipped with a TDR PROM (Campbell Scientific,

Logan, UT) via a Campbell Scientific SDMX50 multiplexer. The cable tester transmitted an electromagnetic wave along stainless steel rods and then measured the propagation velocity. The resulting velocity was related to the relative dielectric constant of the soil which was highly sensitive to the volumetric water content and weakly sensitive to the soil types. The balanced wave guides (probes) in field study *No1 consisted of pairs of 30 cm stainless steel soil rods 50 mm apart (rod diameter = 5 mm). The probes were installed vertically at two depths, 10 to 40 cm (denoted as shallow) and 40 to 70 cm (denoted as deep) below the soil surface. To avoid installing shallow probes in a disturbed soil, the shallow and deep probes were not installed one above the other but with a horizontal separation. The moisture variation within the 10-cm layer below the soil surface was not monitored in order to avoid preferential flow along wave guides located just below the soil surface and their damage by manual and agrotechnical operations. A gypsum resistance block (Watermark, Irrometer Co., Inc., Riverside, CA) was installed close to each TDR probe to monitor the suction head. The plot consisted of 12 trees in three rows. The distance between the trees was 4 m, between rows, 6 m. Four TDR probes and four gypsum blocks were installed on opposite sides of each tree symmetrical to a line passing between the trunk and the irrigation emitter, which was located at 60 cm from the tree trunk (Fig. 1). Both soil moisture content and suction head, were measured automatically every 2h over an entire irrigation season (summer). The TDR probes were connected via a 50 Ω coaxial cable to the multiplexer. Gravimetric measurements of the soil samples were also performed and compared with the TDR readings.

A multiplexed TDR system with 64 probes was used to monitor variations in the soil moisture content every 0.5 or 1 h, depending on the time needed to scan through all the probes. The high density of the
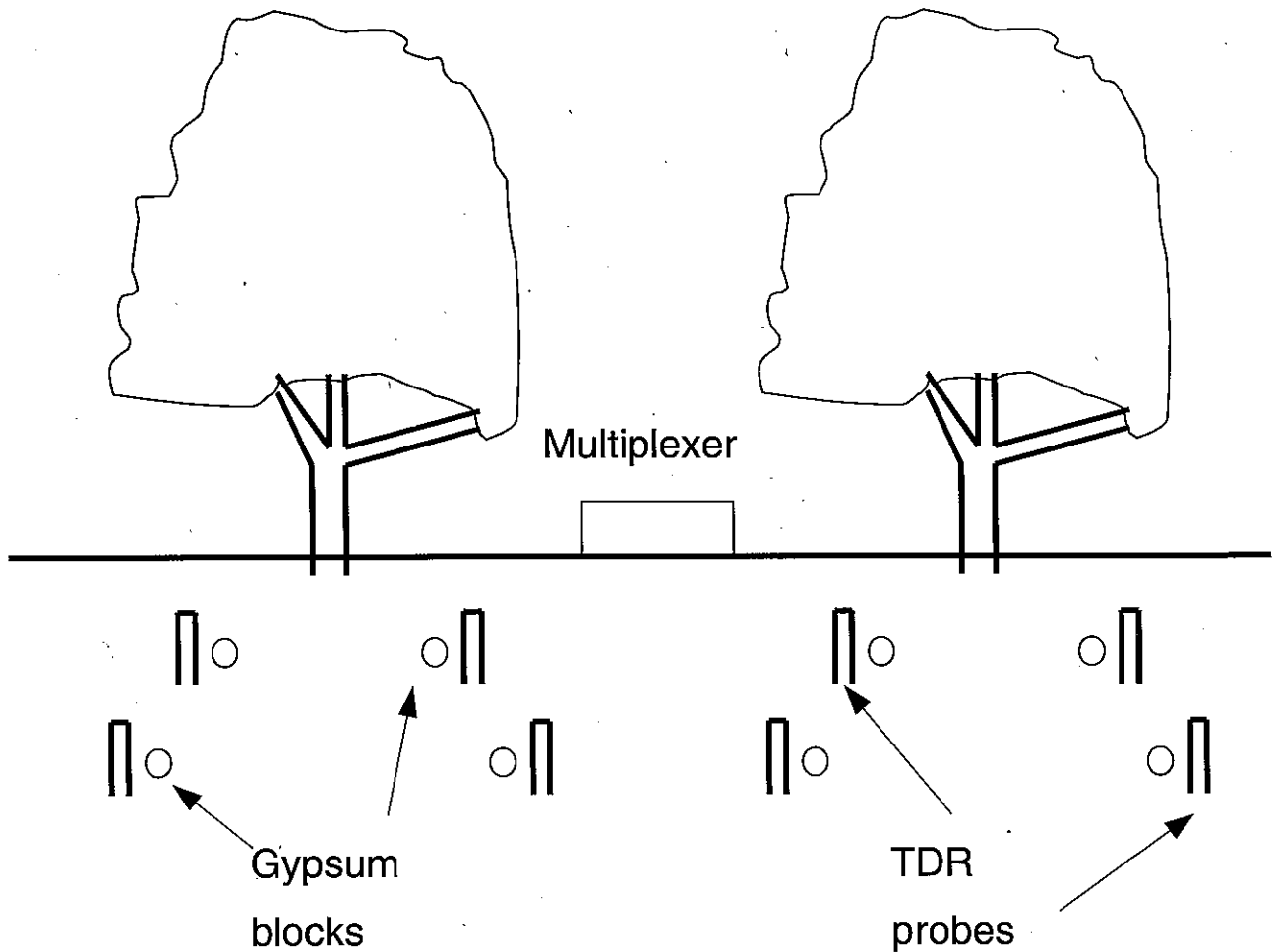

Fig. 1   Trees, TDR probes and gypsum blocks setup in field study No1.

drippers along the pipes and of the plants in the rows enabled us to assume that water sources and sinks were uniformly distributed along the row axis. Thus, the TDR probe installation was designed to measure the variation in soil water with time in a plane perpendicular to the crop row (Fig. 2). The probes consisted of two 15 or 30 cm long rods placed 5 cm apart and inserted vertically. It was assumed that each probe measured the average soil water content in a grid cell that was 10 cm wide and 15 or 30 cm deep, centered on the symmetrical axis of the two rods (see Fig. 2 cell A1). Note that the distance from each rod to the center and the edge of the cell was 2.5 cm). Grid cells A1-A5, B1-B5 and C1-C5 were designed to cover the irrigated range of the rooted soil profile from which root uptake was taking place. Cells D1 and E1 were set up to monitor the soil water content below the root zone within the irrigated range or within the root zone but outside the irrigated range, respectively (Fig. 2), where root uptake was not expected to occur. The TDR sensors did not monitor the soil water content at a depth of 0 to 5 cm, because absorbing roots are very sparse in this layer. Instead, the soil water content in that layer was measured at the beginning and end of each irrigation cycle by oven-drying and weighing undisturbed soil samples taken at positions related to the TDR sensors.

Total water uptake by the plants in field study No2 was measured with a heat-pulse system (Cohen *et al.*, 1988) calibrated for corn plants (Cohen and Li, 1996) on 10 adjacent plants located above the TDR probes.
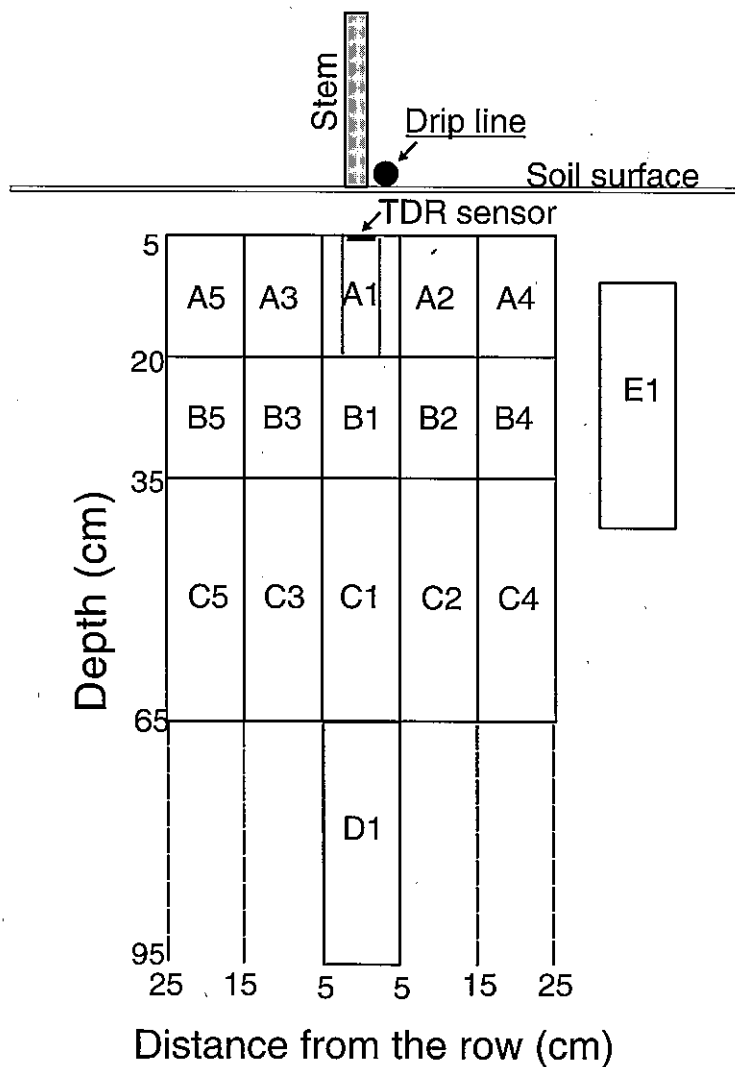

Fig. 2   Layout of the imaginary grid cells formed by the TDR probes in a plane perpendicular to the crop row and drip line in field study No2.

The heat-pulse sensors were installed at the base of the plants to measure the total water uptake. Heat-pulse control, data acquisition and processing were carried out with a data logger (CR-7, Campbell) every 15 min.

Results and discussion

A basic tool for studying and analyzing soil moisture dynamics within the root zone and its availability to plant roots is to follow up its transient variations at different depths. These data are satisfactorily provided by the TDR system. A typical pattern of soil moisture variation versus time between two successive irrigations is shown in Fig. 3. Polak and Wallach (2001) suggested the existence of a qualitative division of the moisture content variation between successive irrigation events into four stages. The first stage takes place during water application, when the moisture content increases markedly to a peak value (Fig. 3). The second stage starts when irrigation stops. Moisture content decreases sharply during this stage, mainly owing to free drainage. During the succeeding stage, moisture content decreases moderately due to the simultaneous occurrence of the diminishing free drainage and root uptake. Polak and Wallach (2001) designated it as the third stage. Distinction between the second and third stages is not always possible, especially in coarser soils where free drainage is relatively rapid and there are noticeable differences between depletion rates during the day and night hours. During the fourth stage, since the soil moisture is solely depleted by root extraction, the pattern of moisture variation during this stage is therefore of significant importance to estimate water availability and for irrigation scheduling design (Polak and Wallach, 2001). Lines were fitted in Fig. 3 to the transient soil moisture variations at the different stages. These lines represented the average slope of soil moisture depletion. The fluctuations around the average slopes were mainly due to variations in water uptake rate during the day and night hours, and to the system's noise. The approximately constant moisture decrease rate during the fourth stage indicated that soil moisture availability
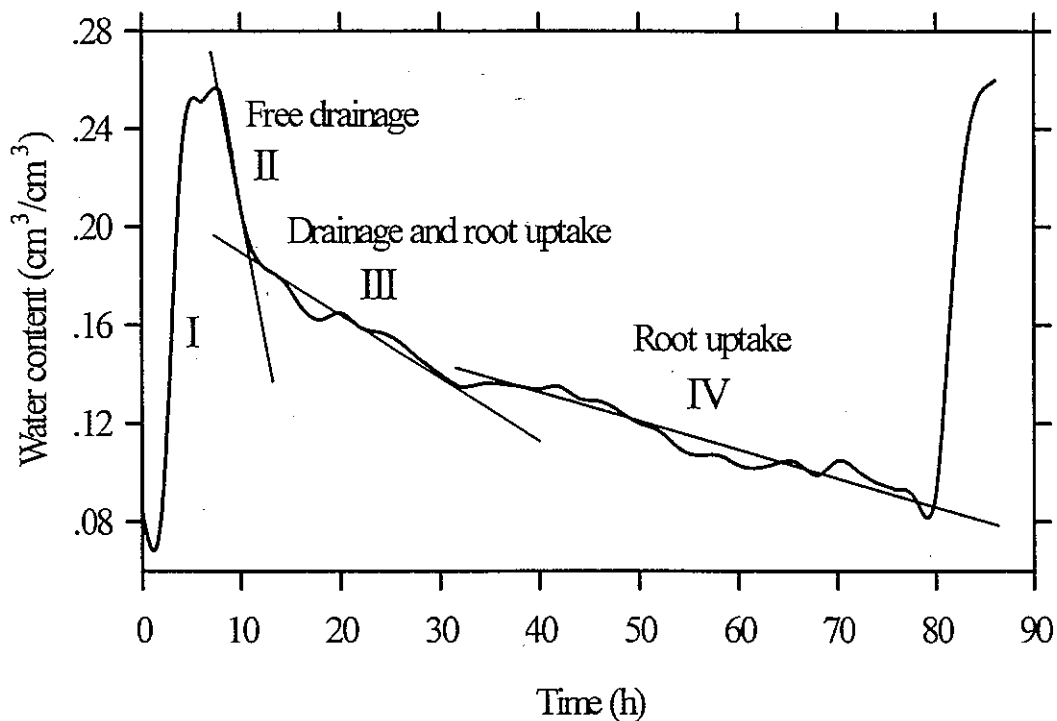

Fig. 3 Variation of moisture content with time during and between two irrigation events measured with a single TDR probe.

met the plant's water demand under the actual meteorological conditions. When the slope of the moisture content variation with time started to decrease under constant atmospheric conditions, soil water became less available. Soil water was then either taken from deeper layers, depending upon availability, or the plant adjusted itself to the stressful conditions.

The TDR data were used in both field studies to analyze the effect of soil moisture changes on the transient and spatial variations in root water uptake rate. The variation of the soil water content in three different layers during three irrigation cycles in the corn experiment (field study No2) is shown in Fig. 4. The range of moisture variation in the upper layer was much wider than that in the second and third layers. The patterns of moisture variation especially during the second and third days can be analyzed by the scheme presented by Polak and Wallach (2001) and shown in Fig. 3. This pattern indicates that the rate of moisture depletion in the upper soil layer decreased during the day hours of the second and third days after water application, which indicates that water became less available. A similar pattern was obtained in field study No1.

Moisture extraction by roots depends on the momentary atmospheric conditions and soil water availability, which in turn depends on the resistance to water flow from the soil bulk to the soil-root interface, and water flow across the root tissues and into the root xylem. Moisture depletion in the rhizosphere induces water flow from the surrounding soil volume to replenish the depleted water. This flux depends on the momentary value of the hydraulic conductivity within the soil volume that encircles the roots and on the hydraulic head gradient between this soil volume and outer surface of the roots. The momentary balance between the actual water flux from the soil volume surrounding the roots and the potential water extraction rate (which depends mainly on the momentary atmospheric conditions) determines whether soil moisture is fully available to the plant. By "fully available" we mean that the water extracted from the vicinity of the root can be fully replenished in a matter of moments. When the root rhizosphere cannot be immediately replenished, water uptake by the roots will be limited by the transport ability of soil water toward the roots, i.e. by the conductivity of the rhizospheric soil.
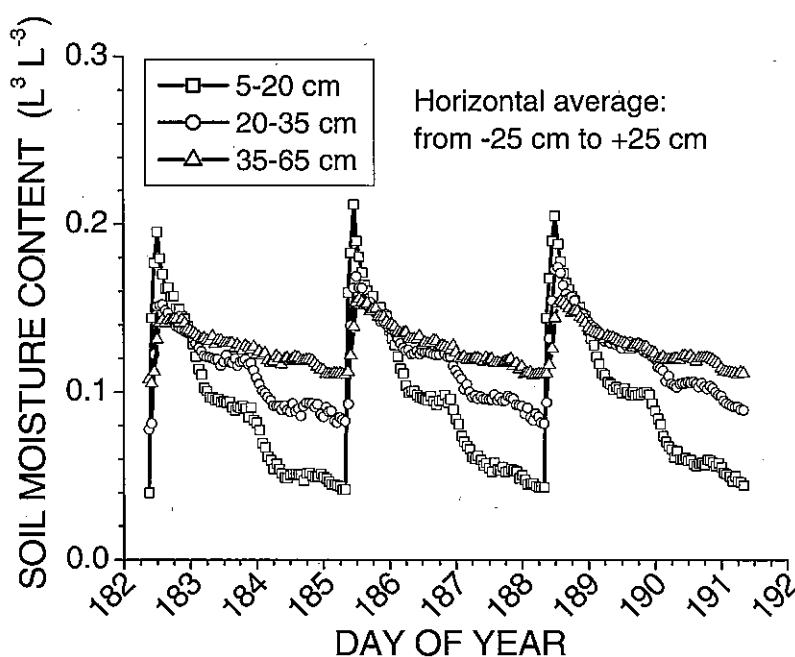

Fig. 4   Evolution of the soil moisture content during three successive irrigation cycles in field study No2.

Owing to the nonlinear relationship between the hydraulic conductivity and moisture content, $K(\theta)$, a deviation from a certain value of (induced a moderate decrease in K, while a similar deviation from a lower value of (induced a sharp decrease in K. No methods of estimating water availability by directly measuring (or $K(\theta)$ near the roots are available. Thus water availability needs to be related to other measurable soil bulk properties. We postulated that $K(\theta)$ of the soil bulk indicates the availability (amounts and rates) of soil water to plant roots. The variations in $K(\theta)$ at different locations in the soil profile were obtained in the current study by the θ (t) measurement and by using the soil characteristic curve, $K(\theta)$. This hypothesis was supported by a comparison of the simultaneous temporal variations of $K(\theta)$ and root extraction rates within the different cells. The hydraulic conductivity relative to the hydraulic conductivity of the saturated soil, $K_r(\theta)$, was estimated from the retention curves measured for soil samples taken from the three layers of field study No2.

The simulated root uptake rate (expressed as mm h^{-1}) for three successive irrigation cycles is compared in Fig.5 with the transpiration rate as measured by heat pulse. The agreement between the two methods indicated the reliability of the TDR measurement and its conversion to uptake intensity.

The simultaneous variations in the moisture depletion rate and relative hydraulic conductivity, K_r, in the different cells of field study No2 are shown in Fig. 6. The variation of K_r was higher and steeper in the cells where the root density and initial moisture content were high (e.g. A1, A2) and it varied moderately in cells where the root density and/or initial moisture content were low. Although K_r in cells A1, A2, and B2 varied by three orders of magnitude during the 3-day period, the rate of water uptake started to decrease relative to its value for similar conditions on previous days only when K_r reached approximately a value of 0.002. This
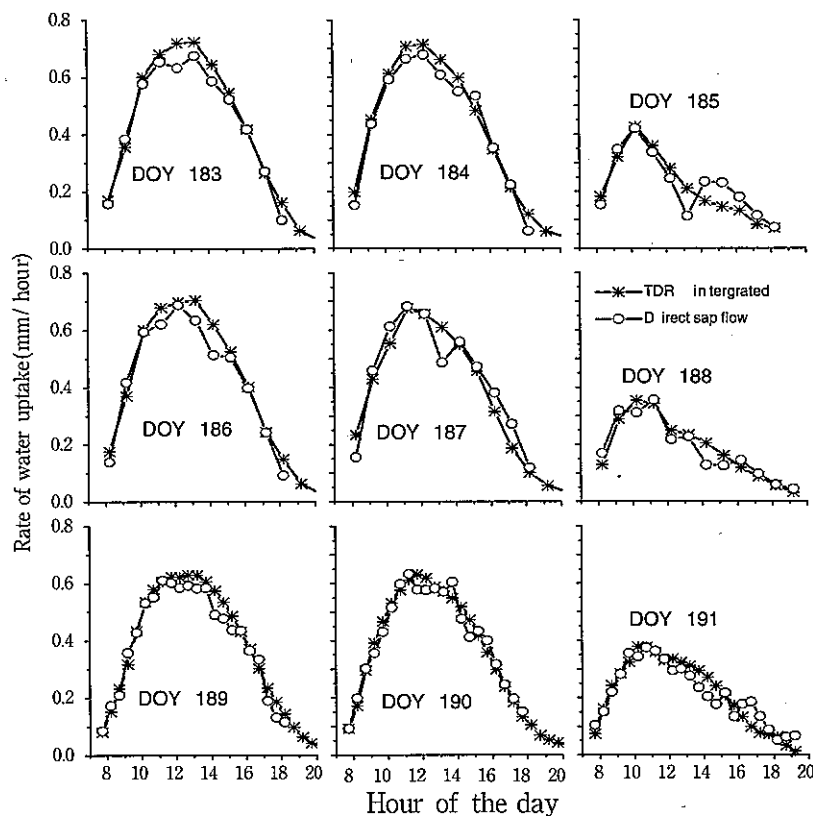
Fig. 5 Transpiration rate during three irrigation cycles (DOY183-191, 1997) directly measured by the heat-pulse method and estimated from the TDR readings in field study No2.

occurred in cell A1 during the late morning hours of the second day and in cells A2 and B2 during the night between the second and third days. In other cells where K_r did not reach this critical value, the water extraction rates maintained their characteristic variation and generally increased the amplitudes of diurnal uptake (A4, B1, B4, and C4 in Fig. 2). This increase can be explained by the lowered leaf water potential in reaction to the general drying of the root zone (Cohen et al., 1983), or by the lowered root water potential in reaction to the diminishing water availability in the high root density cells near the plant base (Klepper, 1990). Thus, one may conclude that for uniform soil there is a critical value for which the bulk soil resistance becomes the limiting factor for root uptake rate. This value for the sandy soil used in the current study was $K_r = 0.002$.

Conclusion

The hypothesis presented and validated in two field studies is that the role of the bulk soil resistance in spatial and temporal variations of the root uptake rate between consecutive irrigation events can be related to a single soil parameter - $K(\theta)$. This parameter is the opposite of the bulk soil resistance to moisture flow since water flux and $K(\theta)$ are linearly related in Darcy's law. The measured results indicated that when the soil water is highly available, the spatial distribution of the root density exerts the main effect on the typical
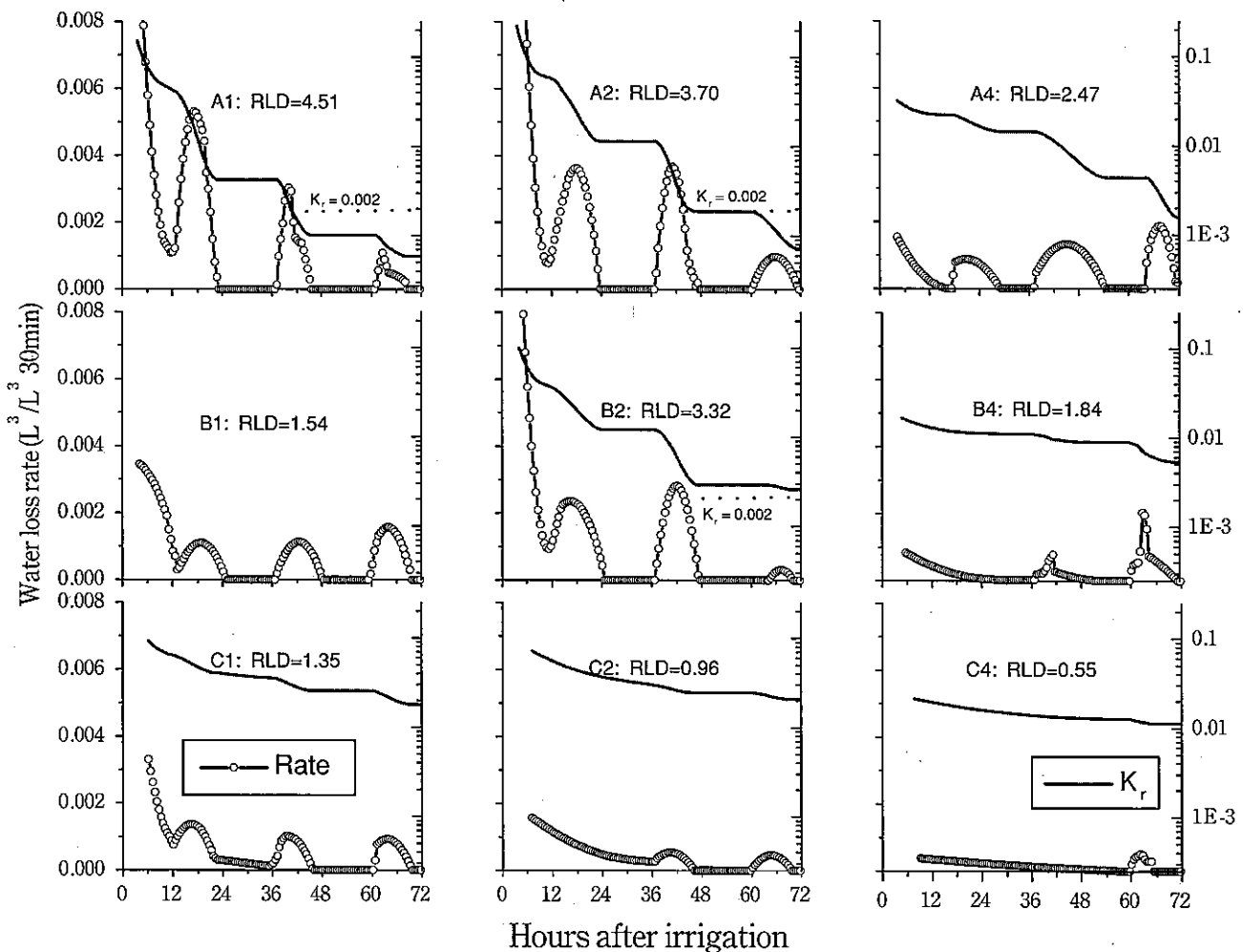

Fig. 6 **Transient variation of the moisture extraction rate and relative hydraulic conductivity of the soil during the 3-day period following irrigation in field study No2.**

pattern of root extraction, in addition to the fact that roots near the plant base are more effective than those farther away. However, when soil water becomes a limiting factor at certain locations near the plant base, the downward and lateral shifting of the typical root uptake pattern with time is clearly related to the spatial and temporal variations in K(θ) above and below a critical value. Continuous measurement of θ (t) at different points within the root zone by the TDR probes enabled us to calculate the spatial and temporal variations in K(θ) and to predict when and where water availability will decrease below the critical value. These results strongly suggest that the initial cause of the spatial evolution of root water patterns is the decreased K(θ) of the bulk soil where the roots are most active after irrigation. Namely, when K(θ) in the upper and center cells falls to a certain level, uptake from those cell decreases, and in response, the plant will lower its leaf or root water potential to extract more water from cells whose K(θ) remains above the critical value. This conclusion is in agreement with a greenhouse study where two soil substrates with different hydraulic properties were examined.

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