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Cover Page

BARD Project Number: IS-3823-06

Date of Submission of the report: 28/2/11

Project Title: Soil Environmental Effects on Root Growth and Uptake Dynamics for Irrigated Systems

Investigators

Institutions

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Keywords *not* appearing in the title and in order of importance. Avoid abbreviations.

Electrical resistivity tomography; heat pulse probe

Abbreviations commonly used in the report, in alphabetical order:

Electrical resistivity tomography (ERT); heat pulse probe (HPP); time domain reflectometry (TDR); time domain transmittance (TDT);

Budget: IS: \$157,000

US: \$187,000

Total: \$344,000

Signature
Principal Investigator

Signature
Authorizing Official, Principal Institution

03-2011

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Publication Summary (numbers)

	Joint IS/US authorship	US Authors only	Israeli Authors only	Total
Refereed (published, in press, accepted) BARD support acknowledged		6		
Submitted, in review, in preparation		1	2	
Invited review papers				
Book chapters				
Books				
Master theses			1*	
Ph.D. theses			0*	
Abstracts			6	
Not refereed (proceedings, reports, etc.)				

* partial support for one additional MSc and one PhD

Postdoctoral Training: List the names and social security/identity numbers of all postdocs who received more than 50% of their funding by the grant.

Dr. Ahmad Moradi (UC-Davis)

Dr. Navin Kumar Twarakawi (UC-Riverside)

Dr. Masaru Sakai (UC-Riverside)

Dr. Sasha Iden (UC-Riverside)

Cooperation Summary (numbers)

	From US to Israel	From Israel to US	Together, elsewhere	Total
Short Visits & Meetings	3	3	1	7
Longer Visits (Sabbaticals)	0	0	0	0

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Description of Cooperation:

In order to understand the complex root zone system, we focused on two objectives: (1) development of measurement tools to monitor in-situ water and nutrient distribution and (2) development of a modeling framework to characterize the plant root and soil system. Our collaborative efforts were directed, keeping these objectives in mind. Both teams worked on instrumentation: electrical resistivity (ERT) in Israel and heat pulse probe (HPP) in the US. A modeling framework was developed by the US team, whereas experiments were conducted by both. Experiments by the Israeli team were focused on irrigation scheduling, whereas the US team is investigating compensated root water uptake.

The researchers from both countries met several times, both in dedicated visits and at other locations, including San Francisco during the AGU annual meeting, Vienna during the EGU annual meeting. In addition, Tamir Kamai, a PhD student at UC-Davis, met several times with the Israeli researchers, both in the US and in Israel. Researchers from same countries were working at very close interaction.

Patent Summary (numbers)

	Israeli inventor only	US inventor only	Joint IS/US inventors	Total
Submitted				
Issued (allowed)		1		1
Licensed				

A. Tuli, J.W. Hopmans, T. Kamai, and B.D. Shaw. 2009. In-situ soil nitrate ion concentration sensor. US patent application serial no. 12/267,895. Pub. No.: US2009/0166520 A1

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BARD research IS-3823-06 Soil Environmental Effects on Root Growth and Uptake Dynamics for Irrigated Systems

Abstract

Root water uptake is perhaps the most important unknown in the mass balance of hydrological and agricultural systems. The understanding and the ability to predict root uptake and the way it is influenced by environmental conditions has great potential in increasing water and fertilizer use efficiency and allowing better control of water and contaminant leach towards groundwater.

This BARD supported research is composed of several components, including a) intensive laboratory work for the quantification of root uptake and the way it is controlled by environmental conditions; b) development of tools for laboratory and field use that can help in sensing very low water fluxes and water content, which is a necessity for studying root uptake; c) development of capabilities to model compensated root uptake; and d) development of a database that will allow calibration of such a model. In addition some auxiliary research was performed as reported later.

Some of the components, and especially the modeling and the HPP development, were completed in the framework of the project and even published in the international literature. The completed components provide a modeling environment that allows testing root compensated uptake modeling, a tool that is extremely important for true mechanistic understanding of root uptake and irrigation design that is based on mechanistic and not partially based myth. The new button HPP provides extended level of utilization of this important tool.

As discussed below, other components did not get to maturity stage during the period of the project, but comprehensive datasets were collected and will be analyzed in the near future. A comprehensive dataset of high temporal and spatial resolution water contents for two different setups was recorded and should allow us understanding of the uptake at these fine resolutions. Additional important information about root growth dynamics and its dependence in environmental conditions was achieved in both Israel and the US.

Overall, this BARD supported project provided insight on many important phenomena related to root uptake and to high resolution monitoring in the vadose zone. Although perhaps not to the level that we initially hoped for, we achieved better understanding of the related processes, better modeling capabilities, and better datasets that will allow continuation of this effort in the near future.

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Achievements

Of the many components of the subsurface water balance, which is the core for understanding agricultural and hydrological systems, root water uptake is the one component that is least understood. The major goal of this research was to develop tools that will allow direct or indirect measurement of root water uptake at the continuum scale, and to relate these measurements to the environmental conditions faced by the root system and primarily spatial and temporal availability of water. This approach is different from the more common physiological approach that tries to achieve understanding of the root uptake based of root and near root conditions.

The research plan was composed of two major components, the addressing directly root uptake and the second addressing root uptake compensation. Two secondary components of the planned research, not necessarily declared explicitly, included the further development of the heat pulse probe (HPP) and the adaptation of electrical resistivity tomography (ERT) to small scale mapping of the subsurface.

Compensated root uptake modeling

Plant root water and nutrient uptake is one of the most important processes in subsurface unsaturated flow and transport modeling, as root uptake controls actual plant evapotranspiration, water recharge and nutrient leaching to the groundwater, and exerts a major influence on predictions of global climate models. In general, unsaturated models describe root uptake relatively simple. For example, root water uptake is mostly uncompensated and nutrient uptake is simulated assuming that all uptake is passive, through the water uptake pathway only. We have developed a new compensated root water and nutrient uptake model (Šimůnek and Hopmans, 2009) and implemented it into the HYDRUS-1D (Šimůnek et al., 2008) and HYDRUS (2D/3D) (Šimůnek et al., 2011) software packages.

The so-called root adaptability factor introduced by Jarvis (1989) to simulate compensated root water uptake was adapted also for root nutrient uptake. This factor represents a threshold value above which reduced root water or nutrient uptake in water- or nutrient-stressed parts of the root zone is fully compensated for by increased uptake in other soil regions that are less stressed. Using a critical value of the water stress index, water uptake compensation is proportional to the water stress response function. Using a critical value of the nutrient stress index, active nutrient uptake compensation is proportional to the nutrient stress response function.

The root nutrient uptake model considers either active or passive nutrient uptake or both, is similarly flexible as the root water uptake model. Few model parameters will allow for a large number of modeling options. The model allows for the absence of nutrient uptake, only passive or active nutrient uptake (each uncompensated or compensated), and any combinations of uncompensated or compensated passive nutrient uptake with either uncompensated or compensated active nutrient uptake (see Figure 14). Total root nutrient

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uptake is determined from the total of active and passive nutrient uptake. The partitioning between passive and active uptake is controlled by the a priori defined concentration value c_{max} . Passive nutrient uptake is simulated by multiplying root water uptake with the dissolved nutrient concentration, for soil solution concentration values below c_{max} . Passive nutrient uptake is thus zero when c_{max} is equal to zero. As the active nutrient uptake is obtained from the difference between plant nutrient demand and passive nutrient uptake (using Michaelis-Menten kinetics), the presented model thus implies that reduced passive nutrient uptake is compensated for by active nutrient uptake. While the c_{max} parameter activates the passive root nutrient uptake, the potential nutrient demand R_p initiates the active nutrient uptake. Finally, critical values of the water stress index ω_c and the nutrient stress index π_c activate compensation for root water uptake and nutrient uptake, respectively.

Root water uptake is closely related to the spatial root distribution function when uncompensated water uptake is considered. However, a much weaker correspondence between the spatial root distribution and root water uptake exists for compensated water uptake. Therefore, spatial root distribution has a significant effect on the prediction of actual plant transpiration when uncompensated root water uptake is considered. The effect of the spatial root distribution is much less significant when compensated root water uptake is allowed. We conclude that a priori knowledge of the spatial root distribution in the soil profile is important when root water uptake is considered to be uncompensated.

High resolution root uptake and root system dynamics mapping

Two intensive root uptake monitoring were conducted. In the first (which is the only one originally planned) root uptake was measured using ERT (to achieve high spatial resolution), TDR (to achieve high temporal resolution), and balances (to complete mass balance). Bell peppers at the vegetative stage of their life cycle were exposed to different irrigation schemes differing in the temporal application of the water, resulting in different spatial and temporal distribution of the water in the subsurface. In addition to mapping water content distribution (as a necessary tool to compute root uptake) we mapped the actual root system development by intensive destructive mapping of root density and other supporting agronomic measures.

This experiment suffered from many technical problems and was later repeated with the appropriate changes and modifications. However, few lessons could be learned (in addition to technical lessons). First, the different application rates did create the desired environmental conditions. These differences could be qualitatively sensed using both the ERT and TDR systems. Second, the environmental conditions change also the agronomic behavior of the plant, expressed in faster growth of the root system, and faster development (and higher final size) of the canopy (both height and dry matter weight) for the more evenly distributed irrigation schemes. That is, the existence of higher water contents throughout the root zone and especially at the shallow depths had significant influence on the plant development, leading to higher utilization of water, lesser drainage,

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and faster development (which when considered in a global way means conservation of water).

As mentioned above, the experiment suffered from many technical problems, not all ones that could have been avoided. The experiment was repeated for two irrigation schemes (realizing that pulses and small discharge are similar in their effect) with much more intensive data gathering and different soil. Preliminary analysis of these new data suggest that the approach of ERT monitoring will provide comprehensive and detailed enough dataset to study root uptake.

Development of Button Heat Pulse Probe

Among available soil moisture measurement techniques, the heat pulse probe (HPP) promises to have wide applications, mainly because of its simplicity and sound physical basis, by providing volumetric water content estimation from volumetric heat capacity measurements. The conventional HPP design is constructed from stainless steel needles extending from a plastic sensor body, with typical needle length and diameter of about 28 and 1 mm, respectively, and with needle separation distances of about 6 mm. The likely Achilles' heel of the conventional HPP is the need to insert needles into the soil. Deflection of the needles can largely affect measurement accuracy because of changes in heater-thermistor spacing during installation. As part of the BARD study, we developed and tested a HPP without needles for measuring soil water content, using a ring-shaped heating element and a single central thermistor that are both embedded in the face of a plastic disk (6 mm thick, 16 mm diameter), hereafter called the button heat pulse probe (BHPP). We evaluated the measurement accuracy by heat transport modeling of the BHPP. To simulate the radial heat transfer associated with the BHPP, a numerical model was developed that accounts for heat conduction into the measured medium and through the BHPP sensor body. The heat transport model was validated by comparing simulation results with BHPP measurements in agar-stabilized water, from which the effective ring radius was determined. After validation, the model was used to evaluate hypothetical BHPP measurements in soil, analyzing differences in temperature response as a function of soil water content. Both the ring radius calibration and water content estimations were conducted by parameter optimization using an inverse procedure.

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Detailed description of the research

Background

The vadose zone is extremely dynamic and complex, linking the atmosphere with the groundwater, as a sandwich. The most upper part of the vadose zone contains the soil, where it is subjected to fluctuations in water content and chemical concentrations by infiltration and leaching, water and nutrient uptake by plant roots and evaporation from the soil surface. Understanding of root water and nutrient uptake mechanisms is highly relevant to better predict responses of sensitive ecosystems to climatic change and to better manage agricultural resources under constraints of water limitations and environmental concerns.

The ever shrinking availability of water, nutrients, land, and economic resources require efficient management practices. This is especially true for the arid and semi-arid regions, largely found in both Israel and the western US. The quest for more efficient irrigation and fertilization techniques led to the development of several important irrigation techniques, such as drip irrigation. More recent important developments include also high frequency (semi-continuous) irrigation and fertigation (e.g. *Silber et al.*, 2005; *Shock et al.*, 2005). One aspect that is common to most emerging practices of irrigation is the environmental control of the spatial distribution of root water and nutrient uptake.

Fluxes of water and nutrients across the plant-soil and plant-atmosphere interfaces are mostly empirically determined rather than mechanistically. In part, this is caused by the increasing complexity of biological systems, with their functions and mechanisms of internal transport of water and nutrients (xylem) and assimilates (phloem). Consequently, plant growth and soil water flow models mostly describe water and nutrient uptake in an empirical way, lacking a sound physiological or biophysical basis. This is unfortunate, as the exchange of water and nutrients is the unifying linkage between the plant root and surrounding soil environment. The simplified sink-approach may be adequate for non-stressed plant growth conditions. However, a different and mechanistic approach is required for stressed soil environments where water and/or nutrient resources become limited in part of the root zone. Using this approach, we already are adopting irrigation water and soil management practices that tactically allocate water and fertilizers to the soil, thereby maximizing application efficiency and minimizing fertilizer losses through leaching towards the groundwater.

Understanding the basic concepts of root water and nutrient uptake mechanisms is becoming increasingly more relevant; to better predict responses of sensitive ecosystems to global climatic change and to better manage agricultural resources under constraints of water limitations and environmental concerns. *Hopmans and Bristow* (2002) in their comprehensive review concluded that progress in the advancement of the basic understanding of transport processes in plants is slow, specifically regarding their control by interfacial fluxes at the root-soil. Consequently, water and nutrient uptake in plant growth

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and soil hydrological models are mostly described in an empirical way, often lacking a sound biophysical basis. This is unfortunate, as the exchange of water and nutrients is the unifying linkage between the plant root and surrounding soil environment. The simplified sink-approach is adequate for non-stressed plant growth conditions. However, it has become increasingly clear that a different approach is required if water and/or nutrient resources become limited in part of the root zone, as is largely the case for water-limited ecosystems in arid and semi-arid climates and in modern irrigated agriculture. A thorough understanding of plant-soil interactions and the plant's regulatory functions in managing soil environmental stresses is needed to predict their responses to limited water and nutrient resources. This includes knowledge of crop responses to the availability of spatially distributed soil water and plant-available nutrients, using a multi-dimensional modeling approach.

Basic irrigation techniques (flood and sprinklers) create a relatively spatially uniform distribution of water in the subsurface. In such cases the root distribution depends primarily on the specification of the plants plus factors (e.g. stress) that might delay root growth, but rarely shape it. Advanced irrigation techniques such as drip irrigation create a highly heterogeneous subsurface in terms of soil water content and nutrient availability. Therefore, roots adjust to the new, less natural, conditions. In those cases the availability of water and nutrients becomes more significant. The distribution of roots, and more important their uptake, is dynamic. Naturally, the specifics (genetics) of the plant of interest are important, but it is also significantly controlled by the conditions created by the irrigation and fertilization practices. Examples include but are not limited to: Frequency of irrigation and fertilization; and limited root volume agriculture (at the pot or at the field scales).

The design of efficient management practices requires the ability to quantitatively predict system behavior. However, the dynamics of root uptake are presently not implemented in most models that describe the flow and transport of water and solutes. Current modeling capabilities treat root uptake mostly as a static process or (at best) consider prescribed, environment independent temporal growth. Moreover, during the growth stages of a plant, in many cases a significant section of the plants life, allocation of water and nutrient resources is empirically employed. Therefore, the design of efficient and innovative practices relies heavily on lengthy field experiments that are mostly empirical and often fail to measure the relevant parameters. The successful proposed research will allow much more flexibility in predicting system behavior, during both the vegetative and the productive stages, using numerical experiments to significantly advance innovative irrigation and fertilization practices.

Better understanding of these irrigation practices will help to direct agriculture towards optimum levels that minimize yield losses and maximize crop quality, while limiting environmental impacts. However, to make that reality, it requires fundamental understanding of plant-soil interactions with specific attention to plant regulatory functions in managing stresses. The BARD study focused on both modeling and experimental efforts, designed to evaluate soil environmental stress effects on plant growth. However, because of

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the enormous challenges faced to design and apply innovative experiments, much of the efforts to date have been on the development of the required modeling and experimental methods. Using techniques developed, current experimental efforts are underway to help understand both physical and biological mechanisms of root water uptake under stressed soil water conditions (see ongoing research, below).

Research hypothesis and goals

The scientific background laid in the research proposal is still very relevant. Of the limited developments that were made during this research perhaps worth mentioning are effort made by the group led by Mathieu Javaux in Université Catholique de Louvain/ Forschungszentrum Jülich (e.g. *Draye et al.*, 2010; *Schroder et al.*, 2009; *Javaux et al.*, 2008), targeting both root uptake modeling in various approaches and root water uptake imaging using techniques similar to those used in this research.

The hypothesis behind this research, as stated in the original proposal, is that root uptake mechanisms can be mathematically modeled as a dynamic process that depends on soil, plant and water properties and state variables. It is assumed that the dynamics of root growth and of root uptake are coupled with the dynamics of water flow and solute transport, although the characteristic time scales of the processes are very different. By incorporating these mechanisms into a water and nutrient fate and transport modeling tool, greater predictability of the single plant behavior, and hence also large system behavior, can be achieved.

The overall goals of this research, as defined in the research proposal, are related to improving irrigation and fertilization efficiency by the development of irrigation and fertilization management tools that maximize production, yet minimize adverse environmental effects. Specifically, our goal is to advance the understanding of root-uptake dynamics. This goal is to be achieved by the development and application of state-of-the-art measurement and modeling capabilities. The specific target of this proposed research is to create a three-way coupled model that describes the flow of water, the transport of nutrients (i.e. N), and the dynamics of root uptake of water and nutrients. Specific objectives included a) formulation of rules for state dependent dynamics of root uptake; b) formulation of rules for state dependent dynamics of root growth; c) development of state-of-the-art root growth chambers for monitoring the spatial and temporal dynamics of water and solutes; d) incorporation of root uptake dynamics in a subsurface variably saturated flow and transport model: State dependent dynamics; e) development of continuum, diffusion-like, modeling approach to describe root growth coupled with water flow and solute transport; and f) inverse solution – identification of root uptake dynamics.

In the following we describe the efforts made in addressing the objectives above. Our accomplishments towards a comprehensive understanding of root growth and root water uptake were only partly accomplished. However, our experimental work will continue in

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the coming year(s), and collected datasets will be shared and integrated with the developed modeling framework as developed with support of the BARD funding.

Experimentally based activities

Israel

In the original research plan a single comprehensive experiment was planned. However, for many reasons the outcome of this experiment were problematic and as a result we have decided to conduct a similar though smaller experiment in which the reasons for the general failure of the first experiment were corrected. Many of the results of the first experiment can be used qualitatively to understand the mechanisms of root growth and uptake and their dependence on the environmental condition induced, but quantitative analysis of these results is weak. Some of this qualitative understanding was applied in the design of the second experiment.

High resolution root uptake (#1)

The first experimental set was designed to obtain high spatial and temporal resolution of water content distribution in the root zone of a bell-pepper plant, through which root uptake in similarly high resolution could be obtained. In addition, the dynamics of root growth were monitored throughout the experiment. The experiment focused on the vegetative stage of the plant. To correlate root uptake with environmental conditions three irrigation treatments were considered, where the difference between the three is the temporal distribution of the applied water, creating different spatial and temporal distribution of the water in the subsurface.

The experiment included 12 cylindrical plastic containers of roughly 60 cm height, and 44 cm diameter. Three irrigation schemes were considered, where in each the daily dose of water is identical, but differently distributed in time. The first scheme used a 2 l/h dripper, where water is applied in a single pulse starting 08:00; the second used a 0.25 l/h dripper starting to work at the same time (this discharge was achieved by accurately splitting a 2l/h dripper); and the last used a 2 l/h dripper but the daily dose was split into eight pulses at 0.5 h

Figure 1: representative water content dynamics throughout the day (for July 5th, 2008, starting at 07:00) for the three treatments at depth of 5, 10, 15, 25, and 40 cm below soil surface (for panels a through e, respectively).

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intervals. These different schemes created significantly different environmental conditions in the container. Of the 12 containers, four were used in each treatment, where out of the four one was equipped with TDR probes, balance, and drainage balance; one was equipped with TDR probes and had no plant in it; one was instrumented with 96 ERT electrodes; and a similar one had ERT electrodes but no plant. The ERT containers were supposed to provide the high spatial resolution with the benefit of non-invasive method, while the TDR probes were supposed to provide the high temporal resolution. The containers with no plant were for calibration of hydraulic properties.

We start our short discussion with presentation of the water content dynamics throughout a single day (Figure 1). Clearly at shallow depths the water content for the 2 l/h treatment is highest, but for a very short time. The two other treatments create smaller increase in the water content, but for much longer time. While the numbers in Figure 1 are not accurate (see later) it is clear that from the agronomic point of view, the plant has much longer time to use the water. Further, the high water contents created by the 2 l/h dripper create locally and temporarily very high hydraulic conductivity, resulting in fast drainage of the water beyond the root zone. Figure 2 compares the drainage from the different containers at four different growth stages. It is clear that the 2 l/h treatment creates significantly more drainage in most cases (other than the last stages of the experiment), indicating that significantly less water are available to the plants.

Figure 2: drainage for 25/7/08 (top left; irrigation dose 0.6 l/d), 29/7/08 (top right, irrigation dose 0.8 l/d), 8/8/08 (bottom left; irrigation dose 1.0 l/d), and 15/8/08 (bottom right; irrigation dose 1.2 l/d). Time starts at 07:00

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Different environmental conditions create difference in many aspects of the root growth-uptake dynamics. First, the uptake throughout the day and the uptake throughout the entire vegetative period are significantly different, as can be seen in Figures 3 and 4. Uptake was computed by simple mass balance. Two important things can be learned. First, as can be expected by the water content distribution dynamics, the lower and more (temporarily) evenly distributed application schemes allow higher uptake, and more importantly, allow higher uptake at the very hot part of the day. This leads to a faster development of the plant that gets to maturity (indicated by the peak uptake) about a week earlier than the 2 l/h treatment. This is also supported by the root distribution and canopy (and dry matter) development that are brought in appendix.

Root growth experiment

In parallel to the intensively monitored containers, 36 sacks (12 for each treatment) of similar dimensions were used to map the actual root distribution. Every second week of the experiment 9 sacks (3 from each treatment) were cut at various heights (roughly 10, 15, 25, 35, and 45 cm from the soil surface). Each layer was split into "core" and "perimeter", and washed through a mesh. The root veins were collected and dried at 60 degrees Celsius.

Root mapping results are presented graphically in appendix, together with other agronomic results (canopy height and canopy dry matter). The results indicate that the root system is composed of a small and dense root system near the plant stem (to depth of about 5 cm), and elongated root system that starts at the stem and moves at very shallow angle towards the container edges where it bends down. Two points are important

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to note: first, the horizontal movement of these roots is against any wetness gradient. That is, the roots move into a very dry region (practically air dry sand, estimated water content of very few percents). We hypothesize that as the core root system has sufficient resources the plant can develop according to its genetics. Eventually, at larger depths, this strategy is proven worthy as the root reaches the water that is more available at the container bottom.

Second point is that the plants receiving more evenly distributed irrigation (over longer time, resulting also in larger wetting blub) develop faster and stronger. Figures in appendix indicate the faster growth of both canopy and the root system. Further, the faster development is not limited to the peripheral root system but to the core as well. This is probably as water is energetically more available to the root a) over longer time; b) in larger volume, and specifically, the longer application time allows more capillary driven horizontal flow, which means that the perimeter root system will see these waters faster. As discussed later, the differences between the pulses and the low discharge irrigation schemes are relatively minor.

High resolution root uptake (#2)

Experiment #1 was a relative failure from many aspects, and primarily technically. Above all it appears that the use of relatively coarse sand, while perhaps sharpening the differences between the different irrigation schemes, was problematic for both the ERT and the TDR sensors. In both cases this is because the water content distribution, and especially at the shallow depths, was very narrow causing a) bad contact of the ERT electrodes; and b) limited contact between the TDR probes and the wet zone. As a result many of the electrical measurements had to be rejected, leading to practically not enough good data for ERT inversion (although the measurements, even the rejected ones, did behave properly and in accordance with other measurements, their values could not be trusted; See Stern, 2010). The TDR measurements (as can be seen in Figure 1) showed consistently low values and had to be corrected using models and global mass balances.

In addition, a multiplexer (for TDR measurements) was defected during early stages of the experiment and only 5 channels could be used simultaneously, leading to inability to measure more than one container simultaneously. As a result, a second experiment was carried out in summer 2010 in which many of the problems were resolved. The new experiment considered only two treatments (as the pulses and low discharge emitters show similar behavior in experiment #1), used red sandy soil ("Hamra") instead of the sand, used primarily TDT (Acclima) probes instead of TDR (with support of Decagon Eco probes), and took practically continuous ERT measurements (for each container at a time) including reciprocal measurements.

Altogether, 291 complete ERT surveys plus 72 reciprocal surveys were completed, each composed of 3,094 individual measurements. Electrode quadruples were arranged so that many "reside" in a single layer to allow later the more simple two dimensional inversion. The large number of measurements should allow omitting even significant portion of the

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measurements and still have enough good measurements. The reciprocal measurements, taken always during the night when flow is minimal, will allow better estimation of the individual measurement error, taking in consideration expected error resulting from the somewhat different conditions between direct and reciprocal measurements.

In addition to the ERT data, TDT data was also collected at 5 minutes resolution from 18 TDT probes (16 of which were functioning throughout the experiment) located in the two containers and additional no-plant container (for calibration of soil properties). The ERT and the TDT data (which includes also EC and temperature data) is currently being analyzed.

Auxiliary research

An ERT system (Syscal Pro Switch 96, Iris Instruments, Orleans, France) was bought for the purpose of this research with partial support of this research budget. In order to study the system a preliminary study was conducted to study the water distribution in a grapefruit orchard near Nir Galim, Israel. Two ERT lines were constructed along and perpendicular a tree row, in 1 and 0.5 m electrode separation, respectively. Measurements were collected roughly once a month over a year, and translated into water content distribution using laboratory calibrated petrophysical relations. Figure 5 presents a representative cross section of the orchard

The figure indicates the spatial variability of the water content distribution, which is the combined effect of the source (drip lines), root uptake, and canopy interception of rainfall. Further details are given by Zur (2009). An attempt was made to track root water uptake by high temporal resolution monitoring around an irrigation cycle in September 2008; however, results were not sensitive enough to detect these relatively fast dynamics.

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USA

Development of Button Heat Pulse Probe for improved soil water content measurements

Among available soil moisture measurement techniques, the heat pulse probe (HPP) promises to have wide applications, mainly because of its simplicity and sound physical basis, by providing volumetric water content estimation from volumetric heat capacity measurements. The conventional HPP design is constructed from stainless steel needles extending from a plastic sensor body, with typical needle length and diameter of about 28 and 1 mm, respectively, and with needle separation distances of about 6 mm. The likely Achilles' heel of the conventional HPP is the need to insert needles into the soil. Deflection of the needles can largely affect measurement accuracy because of changes in heater-thermistor spacing during installation. As part of the BARD study, we developed and tested a HPP without needles for measuring soil water content, using a ring-shaped heating element and a single central thermistor that are both embedded in the face of a plastic disk (6 mm thick, 16 mm diameter), hereafter called the button heat pulse probe (BHPP). We evaluated the measurement accuracy by heat transport modeling of the BHPP. To simulate the radial heat transfer associated with the BHPP, a numerical model was developed that accounts for heat conduction into the measured medium and through the BHPP sensor body. The heat transport model was validated by comparing simulation results with BHPP measurements in agar-stabilized water, from which the effective ring radius was determined. After validation, the model was used to evaluate hypothetical BHPP measurements in soil, analyzing differences in temperature response as a function of soil water content. Both the ring radius calibration and water content estimations were conducted by parameter optimization using an inverse procedure.

Figure 6. Button heat pulse probe (BHPP) photographs; (a) ring-shaped heating element, (b) plastic (Delrin) body with central hole and 0.6-mm deep cutaway, and (c) assembled BHPP

A single BHPP was constructed using materials similar to the conventional needle HPP. The cylindrical body of the BHPP consisted of a 15.9-mm-diameter (5/8 inch) and 6-mm-thick acetal Delrin plastic disk. The BHPP uses a ring-shaped heater element, with a thermistor placed in the center of the horizontal plane of the heater. The heater element was shaped by bending stainless steel tubing around a rod. Heater wire was threaded through the

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tubing, and the remaining space inside the tube was filled with thermally conductive epoxy (Figure 6a). Across the measurement face of the cylindrical body, we cut a 0.6-mm-deep circular incision with a radius of 5.5 mm, and removed all body material from the cut towards the outside of the probe body (Figure 6b). This resulted in a 0.6-mm elevated center sill, around which the heater was mounted, allowing for most of the heating element surface to be in direct contact with the medium to be measured. A regulated power supply was used to provide about 12.6 V DC to the heating element, ensuring constant power during heating. thermistor was inserted through a hole in the center of the sensor body and covered with thermally conductive epoxy (Figure 6c).

Heat transfer in the BHPP and surrounding media was simulated by solving the relevant heat transport equation with the COMSOL Multiphysics finite-element software. A vertical cross-section of the BHPP is presented in Figure 7. For optimization, we used the Matlab Optimization Toolbox in conjunction with the COMSOL-Matlab interface. Measured temperature response data were fit to either measured or model-generated data by minimizing temperature residuals using the non-linear least squares Levenberg-Marquardt method.

However, instead of using the complex and computationally-demanding inverse procedure for estimating water content, we may simplify the BHPP data analysis by using the maximum temperature response (ΔT_{max}) only. For that purpose, we analyzed the relationship between the numerically-calculated ΔT_{max} values and corresponding volumetric water content data, as presented in Figure 8 for various temperature measurement errors. This relationship between soil water content and maximum temperature response of the BHPP permits the use of a simple regression procedure to estimate soil

Figure 7: Vertical cross-section through the center (dimensions are in millimeter); Inner and outer diameter (ID and OD) of the stainless steel (SS) tube are 0.838 and 1.27 mm, respectively. The colors red and white mark the SS tube and thermal conductive epoxy filling, respectively

Figure 8: The maximum temperature response (ΔT_{max}) as function of water content from the different datasets: error-free FD, and measurement errors of 0.005 (STD1) and 0.025 °C (STD2)

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water content for a range of soils. Further evaluation of the BHPP for a range of soil types is ongoing.

Evaluation of a newly-designed button heat pulse probe (BHPP) demonstrated the potential for improved soil water content measurements. We showed that measurement accuracy and robustness of the BHPP are significantly improved, compared to the conventional HPP. Furthermore, the optimal placement of the thermistor relative to the radial heater location provides for a significantly larger temperature response as compared to the conventional HPP, thereby increasing the sensitivity of the BHPP to changes in soil moisture. Errors associated with needle deflection were eliminated by design, whereas the water content measurement sensitivity was increased by the central placement of the thermistor. Although the presented $\Delta T_{max}(\theta)$ relationship is strictly valid only for the soil used in this study, the BHPP will likely perform similarly for most soil types. Ongoing research will test the application of the BHPP for soil water content measurements for a range of soil types.

Root Exploration Study

The objectives of the experimental root study were (1) to determine the right plant and soil for compensated root uptake studies under stressed soil water conditions, and (2) maximizing root distribution uniformity, while monitoring root and shoot growth. For that purpose, we chose two wild plant species: Cottonwood (*Populus fremontii*, Pf) and Sunflower (*Helianthus annuus*, Ha). These were selected, as we expect them to be more adaptive to stressed soil water conditions. Both species exhibit a relatively fast germination and initial growth rate and require significant amounts of nutrients (mainly nitrate). The tested soils included sand (Monterey sand, #30 mesh), gravel mix (Schwartzgruber Plaster, having a wide particle size distribution from clay-size to gravel), and a dual-porosity artificial growth media (Profile fritted clay).

Seeds were germinated with DI water. Four days after germination, the primary root was pruned to enhance branching. Using 0.05 M of CaSO_4 for irrigation, the plants were transplanted to the 3 different soil media (Figure 9a). One week thereafter, the plants (with the soil) were transplanted into a 6-inch diameter flexible plastic growth sleeve (Figure 9b through d). Instead of irrigating from the top, a constant water level was maintained at the 50 cm depth (5% Hoagland solution) using a constant head water reservoir connected to a bubbling tube to ensure aeration. The sleeves were perforated and each sleeve was covered with a white plastic material to prevent light effects on root growth. The cottonwood was grown in all three growth media (4 replicates each), whereas the sunflower was grown in the sand and artificial media only (4 replicates each), for a total of 20 growth sleeves.

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Figure 9: Photographs of different growth stages: (a) Transplants in different soil media after germination and pruning; (b) growth media (from top to bottom): sand, fritted clay, and gravel mix; (c) the flexible sleeve setup; and (d) after transplanting the young plants into the sleeves.

Growing conditions in the greenhouse were: radiation of $0-650 \mu\text{mol m}^{-2} \text{s}^{-1}$ (measured with LiCor), temperature between 19 and 32 °C, and relative humidity of 45-52%. During the 3-month growth period, we took weekly measurements of both leafs and roots. Above ground measurements included: leaf number, leaf length and width. Root growth was monitored by tracing roots using a 8.5×11 inch transparency over the sleeve. At the end of the 3-month experiment (flowering stage of the sunflower), soil cores were taken for destructive root measurements of root length density and root mass, and all leaves were collected to determine total leaf area per plant. Ten cm long soil cores (1.5 inch diameter) were taken at depths of 0-10, 10-20 and 20-30 cm. At each depth, we collected soil cores along a transect, with one sample in the center and additional two cores on either side of the center, close to the sleeve edge. In total, we sampled 9 cores per sleeve, for a total of 180 cores.

At the end of the growing period, all cottonwood plants growing in the Profile fritted clay were mite-infested, and close to being dead. Only one sunflower plant survived in the fritted clay. All other plants did well (Figure 10).

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Figure 10: Photographs at the end of the growing season: (a) sunflower (b) cottonwood, and (c) flowering for cottonwood (top) and sunflower (bottom).

Overall, sunflower grew more roots more rapidly compared to cottonwood, as determined from the root tracing experiment (Figure 11). At the end of the growth period, most roots were observed in the top 10 cm and center, whereas no clear patterns could be observed otherwise (Figure 12). We concluded that root distribution is generally non-uniform for both sunflower and cottonwood under the established growing conditions. Cottonwood roots were mostly concentrated in upper 10 cm in the gravel medium, but were more uniformly distributed in the upper 20 cm of the sand.

With regard to the leaf analysis (Figure 13), we conclude that cottonwood had about 3 times more leaves than sunflower, but both had similar leaf area. However, the sunflower leaves developed much faster. No noticeable differences were observed between the soil media type.

Figure 11. Root length as function of time, for the sunflower (Ha) and cottonwood (Pa) for the different soil media

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Figure 12: Average (a) root length density distribution; and (b) root fresh weight.

The root study was not successful in obtaining a uniform root distribution. Alternatively, we are experimenting with chickpea's (see section III). We did find that sand is a suitable soil medium for soil water stress experiments, as the soil matric potential is very sensitive to changing water content, thereby providing for easy control of soil water stress. Also, the sand is much preferred when controlling nutrient and salt concentrations. The latter is the case, because of the uniformity of the sandy material, little adsorption of nutrients and salts, and the high hydraulic conductivity near saturation.

Figure 13: Leaf area as function of number of leaves (bars are standard error), for cottonwood (Pf – left plot) and sunflower (Ha – right plot).

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Modeling based activities

USA

A New Compensated Root Water and Nutrient Uptake Model - Theory and its Implementation into HYDRUS Models

Plant root water and nutrient uptake is one of the most important processes in subsurface unsaturated flow and transport modeling, as root uptake controls actual plant evapotranspiration, water recharge and nutrient leaching to the groundwater, and exerts a major influence on predictions of global climate models. In general, unsaturated models describe root uptake relatively simple. For example, root water uptake is mostly uncompensated and nutrient uptake is simulated assuming that all uptake is passive, through the water uptake pathway only. We have developed a new compensated root water and nutrient uptake model (Šimůnek and Hopmans, 2009) and implemented it into the HYDRUS-1D (Šimůnek et al., 2008) and HYDRUS (2D/3D) (Šimůnek et al., 2011) software packages.

A new compensated root water and nutrient uptake model that is highly flexible and can be applied to various solutes/nutrients has been developed during this project (Šimůnek and Hopmans, 2009). This model can accommodate various root spatial distribution functions, including their temporal variations due to root growth. The water uptake model can be used for any stress response function accounting for the reduction of the potential root water uptake due to the soil water pressure and osmotic potential stresses.

The so-called root adaptability factor introduced by Jarvis (1989) to simulate compensated root water uptake was adapted also for root nutrient uptake. This factor represents a threshold value above which reduced root water or nutrient uptake in water- or nutrient-stressed parts of the root zone is fully compensated for by increased uptake in other soil regions that are less stressed. Using a critical value of the water stress index, water uptake compensation is proportional to the water stress response function. Using a critical value of the nutrient stress index, active nutrient uptake compensation is proportional to the nutrient stress response function.

The root nutrient uptake model considers either active or passive nutrient uptake or both, is similarly flexible as the root water uptake model. Few model parameters will allow for a large number of modeling options. The model allows for the absence of nutrient uptake, only passive or active nutrient uptake (each uncompensated or compensated), and any combinations of uncompensated or compensated passive nutrient uptake with either uncompensated or compensated active nutrient uptake (see Figure 14). Total root nutrient uptake is determined from the total of active and passive nutrient uptake. The partitioning between passive and active uptake is controlled by the a priori defined concentration value c_{max} . Passive nutrient uptake is simulated by multiplying root water uptake with the dissolved nutrient concentration, for soil solution concentration values below c_{max} . Passive nutrient uptake is thus zero when c_{max} is equal to zero. As the active nutrient uptake is

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obtained from the difference between plant nutrient demand and passive nutrient uptake (using Michaelis-Menten kinetics), the presented model thus implies that reduced passive nutrient uptake is compensated for by active nutrient uptake. While the c_{max} parameter activates the passive root nutrient uptake, the potential nutrient demand R_p initiates the active nutrient uptake. Finally, critical values of the water stress index ω_c and the nutrient stress index π_c activate compensation for root water uptake and nutrient uptake, respectively.

Examples demonstrating several important characteristics of the compensated root water and nutrient uptake model have been developed and posted online. These examples show that flexibility in modeling compensation of water and nutrient uptake generally reduces plant stress and allows the plant to meet potential transpiration and nutrient demands, irrespective of local soil water and nutrient stresses. Neglecting the possibility of compensation may cause significant errors in the water and nutrient balances, thus affecting biomass production and predicted crop yields.

Root water uptake is closely related to the spatial root distribution function when uncompensated water uptake is considered. However, a much weaker correspondence between the spatial root distribution and root water uptake exists for compensated water uptake. Therefore, spatial root distribution has a significant effect on the prediction of actual plant transpiration when uncompensated root water uptake is considered. The effect of the spatial root distribution is much less significant when compensated root water uptake is allowed. We conclude that a priori knowledge of the spatial root distribution in the soil profile is important when root water uptake is considered to be uncompensated.

Widely different dynamics of nutrient concentrations in the soil profile were simulated when a wide range of root nutrient uptake models were applied. While the scenario without nutrient uptake led to the increase in solution concentrations, the scenario with only passive nutrient uptake maintained constant soil solution concentrations, whereas all scenarios that involved active nutrient uptake led to nutrient concentration reductions.

Only small differences in the depth distribution of nutrient concentrations were determined for scenarios that considered active nutrient uptake, irrespective of whether passive nutrient uptake was involved. This result indicates that soil nutrient concentration measurements are unlikely to provide evidence about the relative importance of active and passive nutrient uptakes.

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Figure 14: Schematic diagram that illustrates the presented root water (a) and nutrient (b) uptake mechanisms (T_p , T_a , T_{ac} – potential, actual non-compensated, and actual compensated root water uptake rate, respectively; α – water stress response function; ω_c – water stress index; R_p – potential root nutrient uptake rate; P_a – passive root nutrient uptake rate; A_p , A_a , A_{ac} – potential, actual non-compensated, and actual compensated root nutrient uptake rate, respectively; α_{MM} – nutrient stress response (Michaelis-Menten) function; π_c – nutrient stress index).

Modeling electrical flow

We have further modified the HYDRUS (2D/3D) software package so that it can be used to evaluate ERT (Electrical Resistance Tomography) measurements. HYDRUS now can calculate electric potential distribution in the soil profile for transient water content conditions and any location of electrodes supplying the electric current. The updated model will be used to analyze data collected during this BARD project.

Israel

Auxiliary research

Electrical resistivity tomography has many advantages, and primarily its non-invasive non-destructive nature. This is the main reason ERT was so appealing for this research. However, it also has its limitations, mostly resulting from the mathematical procedure involved in the signal interpretation being ill-posed. That is, inverse solution of the governing partial differential equation for electrical flow with appropriate boundary conditions but limited number of measurements (and the fact that all measurements are at the boundary) results

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in a system that has many degrees of freedom, leading to a solution that is both instable and non-unique. To overcome this problem it is common to add constraints to the inversion objective function. These constraints are often not related to the physics (e.g. one of the most common constraints requires smoothness of the solution).

Without getting into details, we propose here a methodology that may increase the accuracy of the ERT inversion by four different means. First, we use a flow model (based on Richard' equation with roughly estimated hydraulic properties) and petrophysical relations to predict the initial guess of the ERT inversion; second, using this model we locally release the over constraining constraints at regions of interest such as wetting fronts; third, we introduce alternative constraints in these regions that are based on the expected hydraulic gradients; and last, we use ERT inversion results to better estimate the hydraulic properties of the soil (and then recursively improve the ERT inversion results). Figure 15 present an example for the increase accuracy in the inversion that can be achieved using the first three components of this algorithm.

The results of this research are promising, and especially the recursive approach. However, in the time frame of this research it did not mature for application to a three dimensional case as required for this research.

Figure 15: four inversion profiles obtained using ordinary constraints (Case #1), introduction of better initial guess (Case #2), local relaxation of constraints (Case #3), and introduction of gradient constraints (Case #4). Further details are given in Bamberger, 2011

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Cooperation

In order to understand the complex root zone system, we focused on two objectives: (1) development of measurement tools to monitor in-situ water and nutrient distribution and (2) development of a modeling framework to characterize the plant root and soil system. Our collaborative efforts were directed, keeping these objectives in mind. Both teams worked on instrumentation: electrical resistivity (ERT) in Israel and heat pulse probe (HPP) in the US. A modeling framework was developed by the US team, whereas experiments were conducted by both. Experiments by the Israeli team were focused on irrigation scheduling, whereas the US team is investigating compensated root water uptake.

Further work

Significant parts of this research will continue with alternative financial support. This includes the analysis of the data obtained in the second comprehensive root uptake experiment in Israel, and neutron radiography experiment conducted in Davis (see appendix). We believe that this field, of understanding root uptake, is far from being fully addressed, to say the least.

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Appendix

Canopy growth and root distribution

Figure A1: canopy height (left) and weight (dry matter, right) for the first Israeli experiment. The advantage of the more evenly distributed schemes is seen almost from the beginning, especially for the pulses scheme

Figure A2: root weight (dry matter) distribution at root zone core (6" diameter) for 6/7/08 (top left), 20/7/08 (top right), 3/8/08 (bottom left), and 17/8/09 (bottom right)

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Figure A3: root weight (dry matter) distribution at root zone perimeter (beyond 6" diameter) for 6/7/08 (top left), 20/7/08 (top right), 3/8/08 (bottom left), and 17/8/09 (bottom right). It is important to note that most roots are at the container edges

Images of the experiment

Figure A4: ERT containers. From left to right, 2 l/h, 0.25 l/h, and pulses

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Figure A5: sack slicing and root mapping

Neutron radiography

Ongoing research is using neutron radiography as an innovative technique to noninvasively measure and monitor root growth and soil moisture has the following objectives: 1) to monitor root response and development in soil with heterogeneously distributed water content and salinity, 2) to localize the active water-uptake zones within the root system and measure the water uptake in different part of the root system under various degree of water and salinity stress, and 3) to apply and test the compensated water and nutrient uptake model.

Applying neutron imaging to soil and plant studies during the last years, we have established a quantification procedure and proper image analysis algorithms to extract the necessary information from the neutron images. We showed that water distribution in soil-root interface is highly heterogeneous and dynamic (Fig. A6). Therefore, the hydraulic properties of the soil-root interface should be measured in situ. It has also been demonstrated that although water can be taken up from all parts of the root system, only some parts of the

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roots might be active in taking up water. Plants might also redistribute water uptake zones within their root system depending on the local environmental conditions that the roots are experiencing. Therefore, a modeling formulations of compensated water uptake has been proposed and implemented (Simunek and Hopmans, 2008). We also developed the required instrumentations and sensors for monitoring water, nutrient and temperature changes in the root-zone of plants. Our results show that the interactions between roots and soil are very dynamic, heterogeneous, and scale-dependent. Therefore, the need to study root water uptake dynamics with high temporal and spatial resolutions.

Figure 1: Neutron radiography of water distribution in a sandy soil with a lupin. The colormap indicates the water content: blue means high water content, red means low water content. The field of view is 15 x 15 cm. Right hand: sample during root uptake, showing that more water is stored next to the roots. Center: sample becoming dry. Left hand: sample immediately after irrigation, showing less water next to the roots. These results demonstrate the specific properties of the rhizosphere.

Chick pea plants will be grown in containers with dimensions of 40x20x1.5cm (see Figure A7, left image) filled with sand for 3 weeks at bay 4 at the McClellan Nuclear Research Center (MNRC) in Sacramento, CA.. Our setup permits the control of soil moisture and nutrients using a porous tube and hanging water column. This way, we are able to provide different water availability in the two parts of the root system in growth containers and at the same time measure the water uptake from each side. The root distribution pattern and the dynamics of soil water will be then determined by neutron radiography. Heat-pulse probes will monitor the nutrient concentration and temperature of the different parts of the root system. The neutron radiography will start when plants have completed the vegetative period (3-4 weeks after plantation). Preliminary results have already shown that the experimental setup with chickpeas will establish a relatively uniform root distribution (Figure A7, right image).

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Figure A7. Experimental setup, schematic of growth-container facing the incident neutron beam (left), and neutron radiography image of chick peas (right).

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