The Root Zone: Soil Physics & Beyond

BARD-Hosted

2016 Kirkham Conference and the Research Workshop of the Israel Science Foundation

BOOK OF ABSTRACTS

Ben-Gurion University of the Negev, Sede Boqer Campus, Israel, 10-14 April

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	Planning for food security: Global perspectives, roots and reserves
20:00	Ensemble Joya

11.4.16 Monday

9:00-9:20	**Welcome and Opening Remarks**
	Naftali Lazarovitch, Ben-Gurion University of the Negev
	Dan Blumberg, Vice-President and Dean for Research and Development, Ben-Gurion University of the Negev
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	Progress in root zone research: A tribute to Don Kirkham
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	Rien van Genuchten, Federal University of Rio de Janeiro
	Going back to our roots
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	Modeling root water uptake and growth in heterogeneous soils
11:30-12:00	Maciej Zwieniecki, University of California, Davis
	Active control of water fluxes in plants
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	Modeling root water and nutrient uptake using a macroscopic approach
12:30-12:45	Valentin Couvreur, Université catholique de Louvain
	An upscaling model describing root radial hydraulic conductivity from cross-section anatomy and aquaporin expression patterns

12:45-13:05 Discussions

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Session 3: Root respiration and soil aeration (Presider: Shmulik Friedman, ARO, Volcani Center)

14:30-15:00 Scott Jones, Utah State University

Considerations for growing plants in the reduced gravity of space: gas percolation and root intrusion effects in porous media

15:00-15:30 Shimon Rachmilevitch, Ben-Gurion University of the Negev

Root respiration in response to abiotic stress and neighbors

15:30-15:45 Indira Paudel, *ARO, Volcani Center*

Quantifying the CO_2 *transported in xylem and soil in grapefruit orchards*

15:45-16:00 Ilan Ben-Noach, *ARO, Volcani Center*

Barrel experiments for evaluating the effects of oxygation of clayey soils on pepper yield and continuum modeling of air injection into the root zone

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Session 4: Solute uptake by roots (Presider: Moshe Silberbush, Ben-Gurion University of the Negev)

17:00-17:30 Hans Lambers, The University of Western Australia

Plant phosphorus acquisition strategies on the world's most phosphorus-impoverished soils

17:30-18:00 Jonathan Lynch, Pennsylvania State University

Anatomics: exploiting root anatomical phenes to develop crops with improved soil resource capture

18:00-18:15 Uri Nachshon, *ARO, Volcani Center*

Soil structure and texture manipulation to control root zone salt distribution

18:15-18:30 Travis Luc Goron, University of Guelph

Root acclimation responses by finger millet to nitrogen starvation

18:30-19:00 Discussions

19:00 **Dinner + Jezart (Jazz Music)**

21:00 **Pub and Music**

12.4.16 Tuesday

6:30-8:00 Early morning walk

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8:30-9:00 Jan Vanderborght, Forschungszentrum Jülich
Combination of root zone process observations with process models

9:00-9:30 Andrea Carminati, Georg-August University Goettingen
Biophysical rhizosphere processes affecting root water uptake

9:30-10:00 Tiina Roose, University of Southampton
Multiscale image-based modelling of plant soil interaction

10:00-10:15 Nele Friederike Richter-Harder, Georg-August-University of Goettingen
Hydraulic conductivity of roots, soil and their interface

10:15:10:35 Discussions

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14:50-15:20 Paul Hallett, University of Aberdeen

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15:50-16:05 Nimrod Schwartz, Université catholique de Louvain

The impact of mucilage exudate on root water uptake: a numerical study

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Direct measurement of hydraulic properties of unsaturated biofilm-affected soils

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9:00-9:20 Or Sperling, ARO, Volcani Center

Temperature gradients within trees assist carbohydrate allocation

9:20-9:40 Moses Kwame Aidoo, Ben-Gurion University of the Negev

Mechanisms associated with the tolerance of bell pepper (Capsicum annuum L.) root zone response to low temperature

9:40-10:00 Elad Levintal, Ben-Gurion University of the Negev

Free and forced convection in high-permeability porous media

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The interconnected rhizosphere

11:30-12:00 Dror Minz, ARO, Volcani Center
The root zone from the microbial point of view

12:00-12:30 Yan Jin, University of Delaware
Plant-growth promoting rhizobacteria enhances plant drought stress tolerance by mediating physicochemical and hydrological changes in rhizospheric soil

12:30-12:45 Rachel Neurath, University of California, Berkeley
Rhizosphere control of soil carbon association with fresh mineral surfaces

12:45-13:05 **Discussions**

13:05-14:00 **Lunch**

14:00-17:00 **Discussion, summary and conclusions (Presider: Jan Vanderborght, Forschungszentrum Jülich)**

Abstracts

April 11, 2016, Monday

Session 2: Water flow and uptake

(Presider: Uri Shani, Hebrew University of Jerusalem)

Mathieu Javaux[1,2], Valentin Couvreur[1], Katrin Huber[1], Jan Vanderborght[2], Harry Vereecken[2], 1. Earth and Life Institute, Université catholique de Louvain, Belgium, 2. Agrosphere, Forschungszentrum Juelich, Germany

Modeling root water uptake and growth in heterogeneous soils

Soil water distribution is intrinsically heterogeneous due to the time and space variability of soil hydraulic properties, boundary conditions (infiltration, drainage, evaporation) and root water uptake. Plants need to deal with this heterogeneity because their transpiration is physically linked to photosynthesis, especially under water deficit conditions. How they cope with it depends on several processes taking place at different sites and scales. Passive root water uptake allows the extraction of water, preferably from locations where its potential is higher. In addition, active mechanisms may be activated such as responsive root growth or a local increase in root permeability. We propose using a 3-D architectural model that solves water flow equations in and between soil and root systems (called R-SWMS) to address how plant roots have access to water. In particular, we focus on new approaches for modeling root growth and active response to soil water status in structured soils. We also demonstrate how upscaled approaches can help define optimal traits for root water uptake in heterogeneous soils.

Maciej Zwieniecki, University of California, Davis, USA, mzwienie@ucdavis.edu

Active control of water fluxes in plants

The exchange of energy and mass between the soil and the atmosphere is often represented as a two-dimensional interface. Terrestrial vegetation, especially trees, adds another dimension that links soil volume (the root system) with the atmosphere (the tree crown), resulting in the intensification of exchange capacity. As plants are living organisms, this exchange is not driven simply by the physical status of the soil and atmosphere but is controlled by organismal activity as well. In fact, research advancing our understanding of plant physiology reveals that transpiration flux is controlled intrinsically at all levels of the plant structure, including roots and stems. Control spans across dimensional scales from subcellular activity to the whole plant and across multiple time scales from responses modifying flux within minutes to processes that require days or weeks. Using a few case studies, including (1) the activity of aquaporins in roots responding to nutrient availability and evaporative demand, (2) the interplay between root growth rate and suberization, (3) variable stem hydraulic resistance due to hydrogel activity in bordered pits and (4) variation due to the embolism/recovery cycle, I will discuss the influence of modifications to hydraulic pathways on whole plant water fluxes and the biological implications of

hydraulic path resistance for plant interactions with the soil environment.

Jirka Šimůnek, Department of Environmental Sciences, University of California, Riverside, CA 92521, USA

Modeling root water and nutrient uptake using a macroscopic approach

Plant root water and nutrient uptake is one of the critical processes in subsurface flow and transport modeling, as root uptake controls actual plant evapotranspiration, water recharge and nutrient leaching to the groundwater. The process also exerts a major influence on the predictions of global climate models. There are two major approaches generally used for the simulation of root water uptake in vadose zone hydrological models, to be applied at the plot or field scale: a ***microscopic*** or mesoscopic approach that considers processes at the scale of individual roots, and a ***macroscopic*** approach that neglects the effects of the root geometry and flow pathways around roots, and formulates root water uptake using a macroscopic sink term that lumps root water uptake processes into a single term of the governing mass balance equation.

The focus will be on the macroscopic approach, on the historical perspective of this approach and then its current state-of-art. I will also discuss the latest ***compensated root water and nutrient uptake model***, which is implemented in HYDRUS. This model is relatively general and allows its users to consider both non-compensated or compensated water and nutrient uptake, and passive and/or active nutrient uptake. It also considers various stresses that can reduce potential uptake to actual uptake. The model uses the so-called root adaptability factor, which controls the extent of compensation in which reduced root water or nutrient uptake in water- or nutrient-stressed parts of the root zone is compensated for by increased uptake in other soil regions that are less stressed. Total root nutrient uptake is determined from the total of active and passive nutrient uptake. The model provides the flexibility to consider either or both of these uptake mechanisms, depending on specified parameters. Finally, I will discuss some recent applications of the macroscopic approach of root uptake.

Valentin Couvreur, University of California-Davis, Davis, CA, USA

An upscaling model describing root radial hydraulic conductivity from cross-section anatomy and aquaporin expression patterns

Objectives: To improve our understanding of aquaporin (AQP) expression patterns and root anatomy effects on radial hydraulic conductivity by combining quantitative *in vivo* and *in silico* experiments from the cell to the root cross-section scales in various hydric environments.

Methods: A program generates explicit 2D root cross-section hydraulic networks from anatomical images. The hydraulic network includes "cell wall" and "intra cell" nodes constituting connected pathways allowing water flow from the root surface to xylem vessels using the transmembrane, apoplastic and symplastic pathways. Cell layers have hydraulic properties that depend on plasma membrane AQP abundance and apoplastic barrier deposition. Water potentials and fluxes are computed from

Darcian flow equations in the network. The cross-section radial hydraulic conductivity can then be calculated.

Results: We created a mathematical model linking the radial conductivities of root segments to a minimal set of quantitative molecular (AQP expression) and explicit anatomical data. The model distinguishes apoplastic, symplastic and transmembrane pathways within the root tissues and integrates the temporal scales of AQP regulation and apoplastic barrier formation, which drive root hydraulic properties.

Interpretation: The data obtained during the project lead to a better understanding of the constraints that drive AQP expression patterns and apoplastic barrier deposition. This new model is intended to replace the empirical rules that were used in pioneer models of water dynamics in the soil-plant system. It is expected to become a tool that will bridge the gap between protein regulatory pathways operating at the cell level, hydraulic behaviour at higher levels, and strategies of plant water use, which constrains the success of crop water acquisition in various drought scenarios.

Session 3: Root respiration and soil aeration **(Presider: Shmulik Friedman, ARO, Volcani Center)**

Scott B. Jones (Utah State University, USA), Robert Heinse, Dani Or, Markus Tuller, Gail E. Bingham

Considerations for growing plants in the reduced gravity of space: gas percolation and root intrusion effects in porous media

The 2015 movie, *The Martian*, highlights thought-provoking aspects of growing plants off-planet in a reduced gravity environment. Much of the challenge, in addition to planting seeds and hoping they sprout, lies in the subtleties of how reduced gravity affects the plant root environment. Plants have been grown successfully in microgravity on board both the Russian and International Space Stations, but not without numerous failed attempts and complications, some of which had to do with maintaining optimal liquid and gas supply to plant roots. Key aspects of the design and delivery of fluids under these conditions are poorly understood due to limited experimental opportunities. Theoretically, the porous medium water content distribution within the vertical profile should be altered in reduced gravity, the extreme case of a uniform distribution being expected in microgravity. This shift in water content distribution raises questions as to the impact on the transport of both liquids (water, nutrients) and gases (O_2, CO_2) in the root zone. Parabolic flight experiments have shown that preferential flows may lead to phase (air or gas) entrapment that would affect both liquid and gas transport. This altered environment is further complicated by the fact that root zones designed for extraterrestrial flight are generally more constrained due to volume and mass restrictions, leading to potentially higher root densities and greater resource demand. Higher root densities could also alter the pore space and thereby modify the anticipated water retention character of the root zone. This complication suggests that a dynamic control set point may be required to adjust for a “moving target” in terms of the management of water content. To address some of these questions, we will present microgravity-measured results of water retention and oxygen diffusion aboard the International Space Station where coarse aggregated baked clay particles were studied. For example, about a 10% reduction in volumetric pore space was observed following rice (Oryza sativa L.) root growth, which could change a well-aerated root zone into an anoxic environment if not accounted for. Numerical modeling of plant transpiration and irrigation using volumetrically controlled water content under different gravity environments revealed similar hydraulic responses in fine-textured porous media typically unsuitable for plant growth in greenhouses. Oxygen diffusion measurements aboard the ISS revealed a potential shift in the gas (O_2) percolation threshold in finer particle-sized media. The apparent reduction in the volume-averaged diffusive transport in microgravity, along with other anticipated alterations within the root zone, may require adjustment in plant-growth system management protocols and model development for the reliable response prediction of reduced-gravity porous-medium systems.

Shimon Rachmilevitch, Ben-Gurion University of the Negev, Israel

Root respiration in response to abiotic stress and neighbors

Plant root respiration is a major component of the carbon budget from the individual to the global scales; however, measurements of root respiration are scarce. The current talk will present three different studies of root respiration and the partitioning of the cytochrome and the alternative pathways in response to high soil temperature, nutrients and non-self-neighbors. Our results shed new light on the assumptions made regarding the quantity of respiration as used in carbon budget models.

Indira Paudel[1,2], Ashar Bar Tal[1], Nativ Rotbart[1,2], Jhonatan Ephrath[3], and Shabtai Cohen[1]

1 Institute of Soil, Water and Environmental Sciences, ARO Volcani Center, Bet Dagan, Israel 5025001, 2 The Robert H. Smith Faculty of Food Agriculture and Environment, The Hebrew University of Jerusalem, Rehovot, Israel, 3 The Ben-Gurion University of the Negev, Israel

Quantifying the CO_2 transported in xylem, as well as the CO_2 efflux from soil, in relation to treated wastewater irrigation and climate in grapefruit orchards

Plant respiration, the main controller for yield and productivity, consumes a large portion of assimilates in orchard-grown trees. A major portion of plant respiration is dominated by belowground metabolism, which largely depends on external climate conditions, management practices, and irrigation water. Further, recent evidence has shown that a significant portion of root-respired CO_2 dissolves in a soil solution and is transported by sap flow, so efflux-based belowground respiration has been underestimated. In this study, we aimed to quantify the effects of external climate conditions and treated wastewater irrigation (TWW) on the levels of xylem sap pH and soil and root-respired CO_2, as well as total autotrophic belowground respiration and its interaction with environmental factors (temperature and irrigation water) and plant physiology (sap flow) on a seasonal scale. We compared and correlated the xylem sap CO_2 concentration to the xylem sap pH, stem and air temperature, and sap flow in fresh water (FW) and TWW irrigated trees in commercial orchards, both in the summer and the winter to early spring seasons. Further, we compared the soil CO_2 flux and xylem CO_2 flux in sap flow, in the irrigation period (summer), and recovery period (winter to early spring) to quantify the impact of irrigation water and external climate conditions on the autotrophic component of belowground respiration and respiratory coefficients (Q_{10}). A large amount of CO_2 was transported in xylem, and was well correlated with xylem sap pH, temperature and sap flow in both seasons and water qualities. TWW and summer increased the total root-respired CO_2 in comparison to FW and winter seasons. As estimated, about twice the amount of CO_2 derived from autotrophic belowground respiration entered the xylem via sap flow as that diffused into the soil environment. These results confirm that root respiration contributed to xylem CO_2 transport, and add to the growing evidence for the underestimation by efflux-based measurements of total belowground autotrophic respirations.

Ilan Ben Noah and Shmulik Friedman, Institute of Soil, Water and Environmental Sciences, The Volcani Center, Agricultural Research Organization, P.O. Box 6, Bet Dagan 50250, Israel

Continuum modeling of steady air injection into partially water-saturated root zones

The problem of steady air injection into root zones described as partially water-saturated, laterally confined soil domains, bounded by either an upper atmospheric pressure soil surface or by a lower impermeable phreartic surface, is analyzed with the help of analytical solutions to the linearized air flow equation. The 3D models were formulated using known mathematical solutions for water flow and adjusting them to describe air flow, assuming a full analogy between the effect of gravitation on water flow and the effect of buoyancy on air flow. Air flow patterns depend on a single soil characteristic parameter, indicative of the ratio between the effects of buoyancy and capillary forces driving the air; high values indicate more upwardly oriented flow. Based on the air pressure distribution and the streamlines outlined by the relevant solutions, we conclude that the effect of the water table below the source on air flow is negligible, especially in cylindrical confinements. Furthermore, the effect of the atmosphere on air flow in a cylindrical domain is also negligible. The proposed models are applicable especially when the air-pressure gradient in the soil is relatively small, and the effect of air compressibility is negligible. The proposed analysis, although not accounting for unstable, non-Darcian air-flow, can be applied for designing root zone aeration systems, i.e., for decision making regarding horizontal locations, depths and injection rates of the air-injection source.

Session 4: Solute uptake by roots **(Presider: Moshe Silberbush, Ben-Gurion University of the Negev)**

Hans Lambers, School of Plant Biology, The University of Western Australia, Australia

Plant phosphorus acquisition strategies on the world's most phosphorus-impoverished soils

Southwestern Australian soils are amongst the most heavily leached and phosphorus-impoverished in the world. This region is also a hotspot of plant species diversity and, therefore, offers unique opportunities to study plant adaptations to nutrient-poor conditions. Some of these adaptations are of great interest to future crops.

A large proportion of species from nutrient-impoverished environments in Australia cannot produce an association with mycorrhizal fungi but, instead, produce either cluster roots (Proteaceae, Casuarinaceae, Fabaceae), dauciform roots (Cyperaceae) or capillaroid roots (Restionaceae). These specialised roots are a phosphorus-mobilising adaptation in structure and functioning; they release large amounts of exudates (carboxylates) in an exudative burst. Cluster-root-bearing Proteaceae in Australia occur on the most phosphorus-impoverished soils; mycorrhizal species inhabit less impoverished soils in this region. Non-mycorrhizal capillaroid roots (Restionaceae) and sand-binding roots (Anarthriaceae, Haemodoraceae) appear to function in a similar way as cluster roots.

Carboxylates not only mobilise phosphorus, but also a range of micronutrients, including manganese. In addition to the well-known specialised carboxylate-releasing roots, there are likely others, and a screening of species in plant communities, as well as in germplasm collections, can be based on an analysis of manganese concentrations in mature leaves.

I will explore what traits the roots of southwestern Australian species have that allow them to function on the world's most phosphorus-impoverished soils, and compare these with what is known about *campos rupestres* in Brazil, a region similarly low in available phosphorus and also a hotspot of plant diversity. I will explore which of these traits might be of interest for the development of more phosphorus-efficient crops and for which soils such traits are the most relevant.

Jonathan Lynch**,** Penn State University, The University of Nottingham

Anatomics: exploiting root anatomical phenes to develop crops with improved soil resource capture

Natural genetic variation for root anatomical phenotypes has untapped potential value in breeding more resource efficient crops, an important goal of global agriculture. Genetic variation for root hair length and density is closely related to P acquisition from low P soils, and is also important for the acquisition of other immobile and mobile nutrients. Several anatomical phenes affect the metabolic cost of soil exploration in maize, including root cortical aerenchyma (RCA), cortical cell file number (CCFN) and cortical cell size (CCS). Root cortical senescence may serve a similar function in barley. Genotypic variation in RCA, CCFN and CCS is associated with water acquisition from drying soil and therefore crop yield under water stress. Genotypic variation in RCA is also associated with N capture and therefore crop yield in low N soil. Root anatomical phenotypes in maize are associated with root penetration of hard substrates, an important component of crop adaptation to drying soils. To exploit such variation for crop breeding, we have developed 'Anatomics', which combines Laser Ablation Tomography (LAT), a novel high-throughput platform for phenotyping plant tissue anatomy, with 'shovelomics', high-throughput field phenotyping of crop root systems. Anatomics is discovering major genes controlling root anatomical phenes in rice, maize, and common bean. Some of these phenes are now being deployed in crop breeding programs in Africa to develop more drought-tolerant, resource efficient crop varieties.

Uri Nachshon; Arbel Berezniak; Alon Ben-Gal, ARO Volcani Center, Israel

Soil structure and texture manipulation to control root zone salt distribution

Soil and water demands for agriculture are constantly increasing to meet the increasing requirements for food by the growing world population. To overcome the lack of good quality water, water sources that in the past were considered unsuitable for irrigation are being used today. Drip irrigation is a useful method for the application of low quality water, as it does not wet the foliage and limits the spread of pollutants. Nevertheless, when using low quality water, drip irrigation may be insufficient for leaching the soil and may lead to its salinization. Recent studies have shed new light on salt dynamics in porous media, indicating preferential salt accumulation within small pores, while larger pores remain free of salt. In this work, this concept was examined in the presence of a growing root system and tested to determine whether the manipulation of soil texture and structure can promote the removal of salts from the root zone.
Lysimeters and Hele-Shaw cells were used in experiments examining water and salt distribution in the soil and root development as tomato plants were irrigated with either brackish or fresh water under various arrangements of soil structure and texture. It was shown that plants whose root system was located in a relatively coarsely textured medium, surrounded by a finely textured medium, and irrigated with saline water grew favourably compared to situations of homogeneous finely or coarsely textured soils. The plants within the complex soil structure had the most developed root systems with the lowest soil salinity values, due to leaching of the coarsely textured medium and the accumulation of salts in the finely textured medium beyond the root zone. The interface between finely and coarsely textured soils acts as a capillary barrier that prevents the return of saline water from the fine medium to the roots. In spite of this, the finely textured medium was found to support relatively high water content in the root zone due to enhanced vapour transport towards the coarsely textured medium.

Travis Luc Goron, University of Guelph, Guelph, ON, Canada

Root acclimation responses by finger millet to nitrogen starvation

Objectives: The small grain cereal, finger millet (FM, *Eleusine coracana*), is reported by subsistence farmers to produce grain even with zero nitrogen (N) fertilizer. The exact mechanisms underlying the acclimation responses of FM to low N stress are largely unknown. The objective of this study was to survey the root morphometric responses of FM, including root hairs, to N starvation.
Methods: Plants were grown in a semi-hydroponic system on clay gravel (containing extremely low background N), supplemented with either very little N or zero N. Plant

roots were quantified with large-area flatbed scanners and novel root hair microscopy. Total root system length, crown root length, average crown root length, and lateral root length were all examined, as well as root hair length and density throughout the entire root system. Correlations of these root metrics to yield and other aboveground measures of plant health were generated.

Results: To our surprise, plants grown without deliberately added N grew to maturity, looked relatively normal and produced healthy seed heads. Plants responded to the low N treatment by decreasing shoot, root, and grain yield, associated with a decreased crown root number, total crown root length and total lateral root length. Changes in crown root number appeared to coordinate the belowground acclimation responses to N. Most importantly, long and dense root hairs were observed throughout the entire root system in stressed plants.

Interpretation: FM possesses a remarkable ability to grow to maturity without deliberately added N. When undergoing N starvation, the root system of FM displayed several interesting attributes with important implications for nutrient flow in the rhizosphere. Our results suggest that the root system of FM may be incredibly dynamic and responsible for the plant's impressive nitrogen efficiency, and should be further explored.

April 12, 2016, Tuesday

Session 5: Root-soil interface and noninvasive measurements (Presider: Alex Furman, Technion, Israel Institute of Technology)

Jan Vanderborght, Agrosphere Institute IBG-3, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany

Combination of root zone process observations with process models

Recently, considerable progress has been made with respect to the development of (non-invasive) measurement techniques that provide information about root zone processes. At the scale of soil cores, non-invasive imaging techniques that visualize root systems, water content distributions, and tracer substances have been further developed and optimized. At larger scales, geophysical methods, root observations in rhizotubes, and water isotope tracing techniques can be deployed to monitor root zone processes. A general problem with root zone observations is that they give only indirect and incomplete information about the processes that are of interest, e.g., root water uptake and its reduction when the root zone runs out of water. Therefore, root zone process models are indispensable for interpreting experimental observations. A problem that arises here is that process models may not be compatible with the information provided by the measurements. This implies that process models need to be developed and adapted so that simulation results can be matched or compared with experimental observations. In this contribution, examples of combining observations with models, the implications for model development and the additional information or insights that can be obtained from this combination will be given. Experiments in which growing root systems in soil cores were monitored with X-ray CT or with MRI and in which tracer distributions were monitored with MRI will be presented. These experimental data were interpreted with a soil-root model that couples flow and transport in the soil and root architecture. At the soil profile and field plot scale, water isotopes and root observations in horizontally installed rhizotubes, together with water content and water potential measurements, were combined with an upscaled version of the soil-root system model to parameterize this model and quantify processes such as root water uptake compensation and hydraulic lift.

Andrea Carminati (Georg-August University Goettingen) and John Passioura

Biophysical rhizosphere processes affecting root water uptake

The flow of water into the roots and the (putative) presence of a large resistance at the root-soil interface have attracted the attention of plant and soil scientists for decades. Such resistance has been attributed to either a partial contact between root and soil, large gradients in the soil matric potential around the roots, or an accumulation of solutes at the root surface creating a negative osmotic potential.
Our hypothesis is that roots are capable of altering the biophysical properties of the soil around the roots, the *rhizosphere*, facilitating root water uptake in dry soils. In particular, we expect that the combined effect of root hairs and mucilage exudation reduces the gradients in water potential around the roots at low soil moistures and high transpiration rates.
Using a pressure chamber apparatus, we measured the relation between the transpiration rate and the water potential difference between the soil and leaf xylem during drying cycles in barley mutants with and without root hairs. At low soil moistures and high transpiration rates, large drops in water potential developed around the roots. These drops in water potential slowly abated after transpiration was decreased. The results suggest that the drop in water potential around the roots was of an osmotic nature. At a critical transpiration rate, the soil could no longer sustain root water uptake, the water content in the rhizosphere decreased and solutes accumulated at the root surface. Root hairs increased the root surface and decreased the amount of solutes per root surface. Mucilage functioned to keep the space between the root hairs moist.
These results demonstrate the importance of the biophysical interactions between roots and soil in modulating root water uptake.

Tiina Roose, University of Southampton, UK

Multiscale image-based modelling of plant-soil interaction

In this talk, I will describe a state-of-the-art image-based model of the soil-root interactions, i.e., a quantitative model of the rhizosphere based on fundamental scientific laws. This will be realised by a combination of an innovative data-rich fusion of structural imaging methods, an integration of experimental efforts to both support and challenge modelling capabilities at the scale of underpinning bio-physical processes, and an application of mathematically sound homogenisation/scale-up techniques to translate knowledge from the rhizosphere to the field scale. The specific scientific question I will address with these techniques is how to translate this knowledge from the single root scale to the root system, field and ecosystem scale in order to predict how climate change, different soil management strategies, and plant breeding will influence soil fertility.

***Nele Friederike Richter-Harder*, Georg-August University Goettingen, Germany**

Hydraulic conductivity of roots, soil and their interface

For decades, soil and plant scientists have discussed the processes that limit water uptake. Reduced water uptake rates in drying soils have been attributed to decreasing soil conductivity, changing flow dynamics in the rhizosphere, the development of resistance at the soil-root interface or inside the root, and the accumulation of solutes at the root-soil interface, with the consequent development of high osmotic pressure. These processes have the potential to limit water availability to plants in relatively dry soils. But measuring these processes at the adequate spatial resolution is challenging. Consequently, our current concepts of how the root-soil interface functions in regulating water uptake are still largely speculative.

The aim of my study is to measure the hydraulic conductivity of the roots and the rhizosphere at varying soil water contents. To this end, I extended the root pressure probe technique, originally developed for roots sitting in water (Steudle 2000), to roots in soils. The technique consists of applying a pressure pulse to the root xylem and recording the pressure relaxation over time. Steady state experiments were also conducted. The extension of the technique to roots in soils required the implementation of a numerical model of water flow and pressure dissipation through the root tissue and the rhizosphere. The experiments were conducted with excised maize roots sitting in water and in relatively dry soil. The pressure relaxation curves with the roots in water and in soil were different, in particular in the second phase of the relaxation. The model suggests that the initial phase of the pressure relaxation depends on the conductivity of the roots, while the second phase is affected by the soil conductivity and the dehydration of the cortical tissue. Further development of this technique will provide simultaneous measurements of the conductivity of the roots, the soil and their interface.

Session 6: Root morphology, architecture and growth (Presider: Alon Ben-Gal, Volcani Center)

***Boris Rewald**,** Hans Göransson, Department of Forest and Soil Sciences, University of Natural Resources and Life Sciences, Vienna (BOKU), Peter-Jordan-Straße 82, 1190 Vienna, Austria. *rewald@rootecology.de

A root is a root is a root? The importance of differentiating between root types

Knowledge of root traits and their plasticity to spatial or temporal environmental conditions will increase our understanding of plant and ecosystem functioning. However, even within root systems, a distinct heterogeneity of traits exists. Thus, detailed knowledge of the traits of individual root types and segments, especially those related to resource uptake, as well as the carbon invested, is key to understanding overall root system functioning. Classification schemes should match functional root types as closely as possible to utilize them for sampling and modelling.

The presentation will summarize the classification systems frequently used in (woody) plants, illustrating differences among root types. Examples will cover water uptake rates by different root types with and without salt stress, and the influence of N fertilisation on root respiration. Further, species-specific differences in root respiration will be outlined, and the diverging activity of key enzymes on different root types will be described. Finally, the consequences of using root type-specific traits for parameterizing terrestrial biosphere models will be discussed in the example of fine-root productivity and turnover.

Alain Pierret[1]
1 Institut de Recherche pour le Developpement (IRD) iEES – Paris (UMR 242),Vientiane, Lao P.D.R. Contact: alain.pierret@ird.fr

The role of deep roots in deep Critical Zone processes

Several examples from the literature record suggest that deep roots could be instrumental in the cycling of nutrients and water (Gewin, 2010; Thorup-Kristensen et al., 2009). For example, there is clear evidence that biological activity extends several meters down into the soil and bedrock (Canadell et al.,1996; Schwinning, 2010; Maeght et al., 2013), thus accessing water and nutrient supplies unavailable to surface roots.
Fine-root production represents about a quarter of terrestrial net primary production globally (McCormack et al., 2015), and although a fresh carbon supply from the roots may induce a 'priming effect' leading to the breakdown of pre-existing soil organic matter by soil microorganisms (Fontaine et al., 2007), there are reports that root-derived carbon is more easily retained in soil than carbon inputs from litter fall (Rasse et al., 2005; Schmidt et al., 2011). Hence root biomass is likely to be one of the main components of the terrestrial carbon budget, and storing more carbon in soils, particularly at depth, could be an effective and readily available means to mitigate climate change. Yet existing estimates of root biomass are overwhelmingly derived from allometric relations, the accuracy of which remains largely uncertain (Yuen et al., 2013). Likewise, current estimates of soil organic carbon (SOC) are almost exclusively based on a sampling depth of 0.3 m (Aalde et al., 2006), even though carbon deposition from deep root growth could be much more substantial than commonly accepted (Harper and Tibbett, 2013).
Lower ecosystem boundaries are deeper and more open, diffuse, heterogeneous and temporally variable than generally thought (Richter & Yaalon, 2012). Plants and associated microorganisms are known to exert feedback controls over the fate of lithology through the exudation of organic acids, ligands and a range of solubilizing compounds that promote the dissolution of minerals and the release of nutrients in plant-available forms (Hinsinger et al., 2011). In addition, the presence of roots at great depth is responsible for the release of CO2, which, while representing only a very small fraction of soil respiration, induces a biophysical magnification of CO2 partial pressures (Jackson et al., 2009), thus releasing cations and generating alkalinity in the hydrosphere. In fine, a marginal fraction of the system's total biomass deep in the profile, i.e. deep fine roots and associated microbes, could have an enormous influence, through respiration, on ecosystem structure and function, directly influencing the rates at which soil that supports the ecosystem itself will form.
Notwithstanding the growing realization that deep roots are a key functional element of the Critical Zone, research efforts devoted to the study of shallow and deep roots remain incommensurate. Despite recent technological advances, observing and measuring deep roots remains challenging, which explains why deep roots have yet to be given the attention they deserve. Consequently, the drivers of deep root growth are still poorly understood, but evidence has accumulated that deep rooting could be a more widespread and important trait among plants than usually considered based on their share of root

biomass. Despite the many hurdles that stand in the way of a practical understanding of deep rooting functions, we anticipate that, in the future, much needed knowledge about the deep rooting traits of a variety of plants and crops will become increasingly influential with respect to how we manage natural and cultivated ecosystems.

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Hinanit Koltai**,** The Institute of Plant Sciences, Agricultural Research Organization (ARO), the Volcani Center, PO Box 6, Bet Dagan 50250, Israel (hkoltai@agri.gov.il)

Strigolactones are regulators of root development and response to phosphate deficiency

Strigolactones (SLs) are a new group of plant hormones and act to regulate different developmental processes in the plant via MAX2, an F-box protein that interacts with the SL receptor. SLs are present in a wide variety of plant species and are synthesized mainly in roots. SLs regulate root system architecture by positively regulating root-hair length and promoting cell number in the primary root meristem. SLs are also involved in the suppression of lateral root formation under sufficient Pi, but in the induction of lateral roots under conditions of Pi deficiency. SL/MAX2 signaling is necessary for the marked increase in root-hair density in seedlings under conditions of phosphate deprivation, which has been associated with an active reduction in actin-filament density and endosomal movement in root epidermal cells. Also, the expression of *MAX2* under the *SCARECROW* (*SCR*) promoter was sufficient to confer SL sensitivity in roots, suggesting that SL signaling pathways act through a root-specific, yet non-cell-autonomous, regulatory mode of action. Application of SLs in agriculture may promote root system architecture and growth for improved crop development.

Sigal Savaldi-Goldstein, Faculty of Biology, Technion, Israel, sigal@technion.ac.il

Regulation of root growth by brassinosteroids

The mechanisms ensuring balanced growth remain an enigma to developmental biologists. To investigate how cellular signals are interpreted at the organism level, we focus on decoding the role of the brassinosteroid (BR) signaling pathway in the cell and tissue types composing the Arabidopsis root. We have established the spatial distribution of BR activity as an important fine-tuning determinant of root growth; in specific cell types, BR signaling drives cell proliferation and cell elongation, while in others, it restrains these processes. For example, BR activity was shown to both delay and promote the onset of stem cell daughter differentiation, when acting in the epidermis, and the stele tissues, respectively. A comprehensive spatiotemporal translatome mapping of Arabidopsis roots was performed to understand the molecular basis of this phenomenon. Analyses of wild type and mutants, featuring different distributions of BR, revealed autonomous tissue-specific gene responses to BR, suggesting its contrasting tissue-dependent impact on growth. BR-induced genes were primarily detected in the epidermal cells of the basal meristem zone and were enriched by auxin-related genes. In contrast, repressed BR genes prevailed in the stele of the apical meristem zone. Auxin was found to mediate the growth-promoting impact of BR signaling originating in the epidermis, whereas BR signaling in the stele buffered this effect. This presentation will emphasize the context-specific BR activity and responses, which are oppositely interpreted at the organ level, as a strategy to achieve coherent growth.

Session 7: Biophysical processes in the soil **(Presider: Pedro Berliner, Ben-Gurion University of the Negev)**

P.D. Hallett, M. Naveed, A.C. Raffan, Institute of Biological and Environmental Science, University of Aberdeen
T. Roose, N. Koebernick, L. Cooper, K.R. Daly, S.D. Keyes, I. Sinclair, School of Engineering, University of Southampton
A.G. Bengough, Division of Civil Engineering, University of Dundee
T.S. George, L. Brown, Ecological Sciences Group, The James Hutton Institute, Dundee

Rhizosphere by design: root traits that physically manipulate soil

Plant roots physically manipulate surrounding soil to ease penetration, provide anchorage, improve water and nutrient capture and enhance gaseous exchange, with knock-on impacts to habitats for microorganisms, soil stabilisation and sequestering of carbon. For agriculture, the societal impacts are crop yields and soil sustainability. In engineering, plant roots have been demonstrated to reinforce unstable slopes, and in ecology, the root-soil interface provides one of the most physically complex and, hence, biodiverse habitats on earth. Root traits that alter soil physical properties include exudates, root hairs, the extent of soil drying and root architecture. This talk will explore the extent to which different root traits physically manipulate soils, drawing on near isogenic crop lines that differ in root hairs, architecture and exudation, and new physical approaches that quantify rhizosphere impacts.
These approaches include hydromechanical testing that bridges soil physics, soil biology

and materials science, in addition to small-scale measurements and non-invasive imaging to measure the rhizosphere directly. For instance, using chia seed mucilage as an exudate analogue, we found 35% decreases in liquid surface tension. In soil:chia exudate mixes, water sorptivity decreased by 50%, the rheological stability of wet soil (flow point and shear modulus) increased by more than one order of magnitude, and dry soil strength increased markedly. As microorganisms use these compounds as substrate, physical properties change further, complicating the understanding of rhizosphere formation. We have started research using harvested root exudates added to soil, which will be followed by smaller-scale measurements that measure the physical properties of the root-soil interface directly. This includes Synchrotron X-Ray CT imaging of root hair mutants of barley, to test the hypothesis that increased root hair abundance and length accentuate rhizosphere formation. Our physically based data will be used to develop and parameterise a model of rhizosphere development, which we look forward to discussing with other conference participants.

Teamrat A. Ghezzehei[1], Nathaniel A. Bogie[1], Ammar A. Albalsmeh[2], Richard Dick[3]
[1]University of California, Merced, [2]Jordan University of Science and Technology, [3]Ohio State University

Rhizosphere hydrodynamics: how do roots modulate flow and transport properties in their immediate environment?

Essential soil-derived resources of terrestrial plants, including water and nutrients, are often scarce and patchy. Therefore, the roots of plants adapted to resource-limited environments must rely on evolutionary adaptive traits that allow them to optimally exploit these scare resources. One such trait is the modification of the rhizosphere via rhizodeposition. Alteration of flow and transport properties of the rhizosphere by mucilaginous material exuded by root tips seems particularly effective in this regard. Here we present mathematical models of the alteration of soil hydrodynamic properties, particularly by increasing water retention potential. This alteration causes the rhizosphere soil to remain at a relatively higher moisture level. We will present the results of modeling studies that elucidate two important services of such rhizopshere alteration. First, we demonstrate that exudates play an important role in facilitating water and nutrient uptake by providing a built-in water potential gradient within the rhizosphere. This phenomenon also results in a fairly wet environment near the roots, which is important for nutrient diffusion and nutrient cycling. Secondly, we show that exudates facilitate the release of water from roots to a very dry rhizosphere at night, when transpiration is shut down. The latter is a widely documented phenomenon known as hydraulic lift/redistribution. In many dry regions, the hydraulic lift water is likely to be the only source of moisture driving microbial activity and nutrient diffusion. This phenomenon is particularly important for perennial shrubs and trees that must weather long dry spells by acquiring nutrients from the dry near surface soils while relying on deep soil moisture reserves for transpiration. The results of this modeling study suggest that rhizosphere modification is a necessary prerequisite for hydraulic lift. In summary, both modeling studies suggest that rhizosphere alteration by rhizodeposits is an actively controlled adaptation mechanism that permits plants to live in otherwise inhabitable conditions.

N. Schwartz[1], A. Carminati[2], M. Javaux[1,3]
nimrod.schwartz@uclouvain.be
[1]Université catholique de Louvain, Earth and Life Institute, Croix du Sud L7.05.02, 1348 Louvain-la-Neuve, Belgium,[2]Georg August University of Goettingen, Division of Soil Hydrology, 37077 Goettingen, Germany, [3]Agrosphere, ICG-4 Forschungzentrum, Juelich GmbH, Germany

The impact of mucilage exudate on root water uptake: a numerical study

For many years, the rhizosphere, which is the zone of soil in the vicinity of the roots and which is influenced by the roots, has been known as a unique soil environment with different physical, biological and chemical properties than those of the bulk soil. Indeed, in recent studies, it has been shown that root exudates and especially mucilage alter the hydraulic properties of the soil, and that the drying and wetting cycles of mucilage result in non-equilibrium water dynamics in the rhizosphere. While there are experimental evidence and a simplified 1D model for these concepts, an integrated model that considers rhizosphere processes with a detailed model for water and root flow is absent. In this work, we developed a 3D model of water flow in the soil-plant continuum that takes into consideration root architecture and rhizosphere-specific properties. Using this model, we examined the impact of mucilage on water content distribution and root water uptake (RWU).
We show that mucilage temporarily isolates the rhizosphere from the bulk soil. For example, during the rewetting process, the rhizosphere remains drier than the bulk soil, and during the drying process (assuming that the rhizosphere is initially wet), the rhizosphere is wetter than the bulk soil. That means that the initial state of mucilage has a strong impact on the ability of the plant to support the transpiration demand. Furthermore, non-equilibrium dynamics results in a small fluctuation of the rhizosphere water content, allowing plants to better adjust for rapid changes in their environment. Overall, the model presented here is a first attempt to include rhizosphere-specific processes within a detailed soil-plant water flow model. The model provides a tool with which to examine the impact of different rhizosphere processes on water dynamics and RWU under different irrigation practices.

Ravid Rosenzweig[2], Elazar Volk[1], Sascha Iden[3], Wolfgang Durner[3] and Alex Furman[3]

1. Civil and Environmental Engineering Technion-Israel Institute of Technology, Haifa, Israel
2. Geological Survey of Israel, Jerusalem, Israel
3. TU Braunschweig, Braunschweig, Germany

Direct measurement of the hydraulic properties of unsaturated biofilm-affected soils

Soil biofilms are abundant in agricultural soils and play a significant role in the rhizosphere, promoting soil fertility and productivity and altering flow and transport patterns in the vicinity of root veins. While it was shown by numerous works that biofilm in saturated systems can cause a significant reduction in the hydraulic conductivity, only a few studies have dealt with the flow under unsaturated conditions, such as those prevailing in the rhizosphere.
We use here direct measurements of the soil hydraulic properties of soil batches inoculated with real biofilms to investigate and quantify the biofilm effect on the

hydraulic properties of unsaturated soils. We show that biofilms can significantly alter the soil hydraulic properties under unsaturated conditions.
Measurements of the soil's hydraulic conductivity function and water retention curve were performed by using the evaporation method. Measurements were conducted under refrigeration conditions to minimize biofilm growth during the experiment. Data were analyzed by the simplified evaporation method and were fitted to the standard relations of unsaturated hydraulic properties. The results show that the hydraulic properties of biofilm-affected soils differ from those of clean soils. It was found that the hydraulic conductivity of biofilm-affected soils is reduced by up to a half order of magnitude compared to the hydraulic conductivity of clean soil. As the amount of biofilm in soil increases, the hydraulic conductivity decreases. The differences in the water retention curves were less pronounced. While no significant difference was observed in the wet and intermediate ranges of the curves, the soil water retention in the dry range increased when increasing the biofilm amount. Fitting to standard relations revealed that the experimental curves are best described by relations of bimodal pore size distribution. It was shown that as the biofilm amount increases, the weight of the secondary pore system increases.

April 14, 2016, Thursday

Session 9: Rhizosphere heat regime **(Presider: Noam Weisbrod, Ben-Gurion University of the Negev)**

Robert (Bob) Horton, Iowa State University of Science and Technology

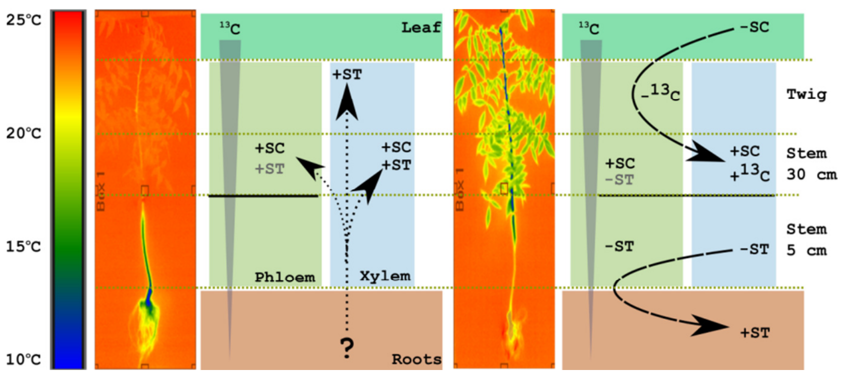
Heat transfer in the root zone: measurements, models, and unresolved questions

Heat transfer in the root zone involves complex mechanisms, and it is dynamic, varying with depth and time. Root zone heat transfer includes surface heat exchange and energy partitioning and subsurface heat transfer. The three active mechanisms of heat transfer are radiation, conduction, and convection. Convection heat transfer includes sensible heat and latent heat components. Soil heat transfer is coupled with soil water transfer. Dynamic heat transfer and dynamic water transfer occur simultaneously. A growing crop has a large impact on radiation exchanges. Crop architecture impacts ground surface shading, and thus, it impacts surface energy partitioning. This presentation reviews measured and modeled root zone surface and subsurface temperatures and heat fluxes. Special attention is given to the impacts of crop canopy shading, soil ridges, and surface mulches on root zone heat transfer. Comments on emerging methods and future needs are included in the presentation.

Or Sperling, ARO, Volcani Center, Israel

Temperature gradients within trees assist in carbohydrate allocation

Seasonal patterns of wood growth and leaf phenology in trees are associated with the availability of non-structural carbohydrates (NSCs). The distribution of NSCs in deciduous trees corresponds to seasonal changes in photoperiod and temperatures. We recognized that it also corresponds to diurnal changes in air and soil temperatures. These frequent changes lead to thermal gradients within trees, but their role in NSC transport remained uncertain. Here we show that temperature gradients within trees affect the rates and direction of NSC allocation by influencing the cellular kinetics of sugar uptake and allocation. Using *P. vera* as a model species, we demonstrate this temperature-assisted NSC transport based on three approaches: an analysis of excised branches; carbon isotope labeling of young trees; and establishing the relationships between temperature gradient and starch levels in mature trees under field conditions. Experiments using three different air-to-soil treatment gradients were applied (T_{air}/T_{soil}: 25°C/25°C; 25°C/10°C; and 10°C/25°C) to simulate summer, spring, and fall conditions, respectively. We found that spring temperature gradients promote bud break by assisting in the allocation of carbohydrates to the canopy before leaves are productive. Conversely, when soil is warmer than air (i.e., fall gradient), sugar transport in xylem is compromised and trees allocate carbohydrate surpluses through phloem to storage in stem and roots. Based on these results, we propose a new model for carbohydrate allocation in deciduous trees, which connects environmental cues and tree physiology by demonstrating that within-plant temperature gradients drive shifts in phenology.



A conceptual summary of our findings from treating L. *pistacia* trees in three temperature regimes: 25/25, 25/10, and 10/25 (canopy °C/root °C temperatures, respectively). The thermic images of the tree demonstrate the temperature gradients within a tree in the 25/10 and 10/25 treatments and the differences in carbon components between these treatments and the control (25/25) are denoted by ± signs.

Moses Kwame Aidoo[1]*, Tal Sherman[2], Aaron Fait[1], Naftali Lazarovitch[1] and Shimon Rachmilevitch[1]
[1]Jacob Blaustein Institutes for Desert Research, French Associates Institute for Agriculture and Biotechnology of Drylands, Ben-Gurion University of the Negev, Midreshet Ben-Gurion, Israel, [2]Syngenta Seed Company, Israel

* Presenter: moseskwa@post.bgu.ac.il

Mechanisms associated with the tolerance of bell pepper (*Capsicum annuum* L.) root zone response to low temperature

In many areas, there is a sharp difference between soil temperatures during the night and the day. These temperatures often reach high levels during the day and drop sharply in the night, which strongly influences root growth and activity and the survival of whole plants. To investigate the mechanisms underlying plant root tolerance/response to low root zone temperatures, we exposed two bell pepper varieties (Canon, CTR1) to three levels of aeroponic root zone temperatures (7, 17, and 27°C). Gas exchange, shoot phenology, root dynamics, respiration and maintenance respiration of shoot and root were investigated. Compared to CTR1, the more root tolerant variety, Canon reduced plant height (51 and 81% at 7 and 17°C, respectively), leaf area (63 and 59% at 7 and 17°C, respectively) and shoot dry weight (61 and 25% at 7 and 17°C, respectively), although stem diameter was significantly higher (24 and 17% at 7 and 17°C, respectively). Low root zone temperature significantly inhibited the gas exchange of the pepper varieties compared to the "optimum" temperature of 27°C; photosynthesis was negatively affected in Canon by 16% at 7°C and 20% at 17°C compared to CTR1. CTR1 displayed higher shoot respiration at 7 (70%) and 17°C (64%) compared to Canon; however, root respiration was lower at 17°C (27%). At low root zone temperature, CTR1 increased maintenance respiration in the shoot and decreased at 27°C; in the root, the opposite occurred. The root dynamics of CTR1 and Canon at 7 and 17°C were significantly affected relative to 27°C. Canon root maximum length was reduced by 8 and 9% at 7 and 17°C compared to CTR1. The root tolerance of CTR1 can be attributed to an increase in shoot respiration to provide the energy required to protect vital organs compared to the less tolerant Canon response to low root zone treatment. The roots also exhibited more tolerance by less allocation of carbon to root respiration and the effective regulation of stomata and cellular carbon assimilation. With this tolerance, CTR1 has the potential to be used as rootstock for low root zone temperature areas.

Elad Levintal[1], Maria Dragila[2], Tamir Kamai[3], Noam Weisbrod[1]

1. Environmental Hydrology and Microbiology, The Zuckerberg Institute for Water Research, The Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Israel, 2. Department of Crop and Soil Science, Oregon State University, USA, 3. Institute of Soil, Water and Environmental Sciences, The Agriculture Research Organization, Volcanic Center, Israel

Free and forced convection in high-permeability porous media

The rate of gas transport within the soil profile and its exchange with atmospheric air has a substantial influence on the gas distribution and concentration in the root zone. Here we study two convection mechanisms that transfer gas at high rates. The first is thermally driven free convection, which develops in conditions of temperature and density gradients. The second mechanism is wind-induced forced convection, which results from surface winds that drive air into the soil. Both of these convective mechanisms transport gas and can be dominant in porous media with high permeability. To investigate these mechanisms, experiments were conducted using large columns filled with high-permeability material made from well-defined single-sized spherical particles. The experiments were carried out under controlled laboratory conditions, where surface winds and thermal differences were both imposed and monitored. A tracer gas of CO_2-enriched air was used to quantify the impact of these mechanisms on gas migration in the porous media. We report our findings on the relationships between the permeability and particle size, and the development and magnitude of convection as a function of thermal differences and surface winds. Results indicate that a permeability range of 10^{-7} to 10^{-6} m^2 is sufficient for the onset of convection under standard atmospheric conditions. A detailed analysis of the column temperature profiles showed that as the thermal gradient changes with depth, convection cells can develop in local sections of the profile, not necessarily reaching the atmosphere. The effect of a 1.5 m s^{-1} average surface wind velocity caused convection to a depth of 0.3 m in most

experimental settings; however, it did not cause additional air circulation at the depth of 0.9 m. The results indicate that both thermally driven and wind-induced convection make a significant contribution to the gas transport in high-permeability porous media.

Session 10: Rhizosphere microbiome (Presider: Harry Vereecken, (Forschungszentrum Jülich)

Mary Firestone 1,4, Shengjing Shi 1,2, Erin Nuccio 3, Zhili He 2, and Jizhong Zhou 2,4
1 UC Berkeley, Berkeley, CA, 2 University of Oklahoma, Norman, OK, 3 Lawrence Livermore National Lab, Livermore, CA, pettridge2@llnl.gov, 4 Lawrence Berkeley National Laboratory, Berkeley, CA

The interconnected rhizosphere

The interactions between plant roots and soil microorganisms have been intensively studied, yet we know little about the interactions among the microbial members of the soil adjacent to roots and how these relationships change over time. To identify potential microbe interactions within the rhizosphere, we used random matrix theory (RMT) based network analysis to identify co-occurrence networks using rRNA gene sequencing over two growing seasons of wild oat (*Avena fatua*), and compared them to patterns in the bulk soil. Bacterial networks in rhizosphere soil were substantially more complex than those in the surrounding soils, and the complexity increased as the plants grew, even as bacterial diversity decreased. Within rhizosphere networks, groups of highly connected modules formed over time, likely representing microbial niches resulting from root-induced changes in environmental conditions, and/or groups of interacting bacteria. As the covariations occurring within modules were generally positive correlations (> 80%), the patterns observed are consistent with extensive mutualistic interactions among bacteria in rhizosphere assemblages. Evaluating the network topology in the context of our previous work identifies quorum sensing as a likely interaction strategy. Highly connected taxa characterized as putative keystone species (module hubs and connectors) often had low relative abundance in the rhizosphere (< 0.1%), which suggests that focusing on abundant taxa may overlook organisms that could play important roles in maintaining rhizosphere community structure and function. Increasing rhizosphere microbial network connectivity and complexity over time represent important characteristics of the rhizosphere microbiome and are previously undescribed properties of these important bacterial assemblages.

Dror Minz[1], Maya Ofek[1,2], Noa Sela[1], Stefan J Green[3], Milana Voronov-Goldman[1,2], Nesli Tovi[1,2] and Yitzhak Hadar[2]
[1]Soil, Water and Environmental Sciences, Agricultural Research Organization, Volcani Center, Bet Dagan, Israel, [2]Robert H. Smith Faculty of Agriculture, Food and Environment, The Hebrew University of Jerusalem, Rehovot, Israel, [3]University of Illinois at Chicago, Chicago, IL, USA

The root zone from the microbial point of view

Studies of plant-root-associated microbiomes have revealed high diversity along with signature host-species-specific and niche-specific associations. The functional implications (ecosystem, plant health) of these associations remain unexplained, however. We have sampled the soil and roots of wheat and cucumber plants growing in identical soil conditions. The soil and plant-associated bacterial community composition was determined using 16S rRNA sequencing. In addition, large-scale metagenome and metatranscriptome sequencing was used to characterize community structure, functional potential and expressed physiological activity. A large database of approximately 2.4 million non-redundant ORFs was assembled from soil and root genomic DNA. The diversity of each habitat's microbes varied widely between niches and between plant species. Based on the metagenomic data, the functional characteristics of soil versus root bacteria deviated dramatically. Soil-to-root functional variations were particularly apparent in specific pathways, including secretion systems, motility, ABC transporters, two-component systems, lipopolysaccharide metabolism and carbohydrate metabolism. In root-associated samples, the metagenomes were functionally similar between the different plant species, despite significant differences in community composition, suggesting that the recruitment of the root community was governed by a basic suite of genes, common to host-colonizing bacteria. Conversely, transcriptional profiles of root-associated communities were non-redundant. For example, high relative expression levels of nitric-oxide reductase genes characterized the wheat root communities, while in the cucumber root communities, the expression of these genes was negligible. An opposite trend was found with respect to catalase and pectinase gene expression. These differences outline the structural, as well as the functional, implications of the host-microbe interactions that are crucial for plant growth, health and development in soil.

Wenjuan Zheng, Harsh Bais, and Yan Jin, Department of Plant & Soil Sciences, University of Delaware, USA

Plant-growth promoting rhizobacteria enhances plant drought stress tolerance by mediating physicochemical and hydrological changes in rhizospheric soil

Enhancement of plant drought stress tolerance by plant growth promoting rhizobacteria (PGPR) has been increasingly documented in the literature. However, most studies to date have focused on PGPR-root/plant interactions; very little is known about PGPR's role in mediating physiochemical and hydrological changes in the rhizospheric soil that may impact plant drought stress tolerance. Our study seeks to advance a mechanistic understanding of PGPR-mediated biophysical changes in the rhizospheric soil that may contribute to plant drought stress tolerance, in addition to plant responses. In this study, we measured soil water retention characteristics, hydraulic conductivity, and water evaporation in soils with various textures (i.e., pure sand, sandy soil, and loam) as influenced by a PGPR (*Bacillus subtilis* strain UD1022) using the instrument HYPROP©. All PGPR-treated soils held more water, and had reduced conductivity and reduced evaporation rates compared to their corresponding controls. While changes in evaporation behavior, i.e., the transition from Stage I to Stage II, due to PGPR addition, occurred in all soils, they differed with soil texture: PGPR prolonged Stage I (but at a lower evaporation rate than the control) in the pure sand, while the bacteria shortened Stage I in the other two soils. These results indicate that PGPR affects evaporation by modifying the soil capillarity and wettability that control liquid phase continuity and the capillary forces that sustain Stage I evaporation. SEM images show that PGPR promoted aggregation (hence broadened pore size distribution) in the pure sand due to EPS production and biofilm formation. On the other hand, the modification of soil wettability by EPS/biofilm, and thus water phase continuity and capillary driving forces, likely dominated the PGPR effects in the other two soils. These findings improve our understanding of rhizosphere functions and have implications for developing biotechnologies using PGPR to increase soil water retention, which would help sustain agricultural production under restricted water availability.

Rachel Neurath[1,2], Thea Whitman[1], Peter Nico[3], Jennifer Pett-Ridge[2], Mary Firestone[1]
[1] UC Berkeley, Berkeley, CA; [2] Lawrence Livermore National Laboratory, Livermore, CA; [3] Lawrence Berkeley National Laboratory, Berkeley, CA

Rhizosphere control of soil carbon association with fresh mineral surfaces

Mineral surfaces provide sites for carbon stabilization in soils, protecting soil organic matter (SOM) from microbial degradation. Our research investigates the intersection of microbiology and geochemistry, and aims to build a mechanistic understanding of plant-derived carbon (C) association with mineral surfaces and the factors that determine SOM fate in soil. Plants are the primary source of C in soil, with roots exuding low-molecular weight compounds during growth and contributing more complex litter compounds at senescence. We grew the annual grass, *Avena barbata*, (wild oat) in a 99 atom% $^{13}CO_2$ atmosphere in soil microcosms incubated with three mineral types representing a spectrum of reactivity and surface area: quartz, kaolinite, and ferrihydrite. These minerals, isolated in mesh bags to exclude roots but not microorganisms, were extracted and analyzed for total C and ^{13}C at multiple plant growth stages. Distribution of ^{13}C on the mineral surfaces was mapped with NanoSIMS and the chemical nature of mineral-associated carbon was evaluated with FTIR and ^{13}C-NMR. We investigated microbial association with soil minerals with next-generation sequencing (Illumina MiSeq) of bacterial/archaeal 16S and fungal ITS. At plant senescence, the quartz had the least mineral-bound C (0.40 mg-g^{-1}) and ferrihydrite the most (0.78 mg-g^{-1}). Ferrihydrite and kaolinite also accumulated more plant-derived C (3.0 and 3.1% ^{13}C, respectively). We found significant differences between the microbial communities on different minerals and bulk soil for both bacteria and fungi. SEM and NanoSIMS imaging revealed high levels of plant-derived C (^{13}C) incorporation in some mineral-associated fungi. Microbial community assembly on mineral surfaces was controlled by mineral type. Our research shows that both soil mineralogy and the chemical character of plant-derived compounds are important controls of the mineral protection of SOM.

Poster Abstracts

Session 8: Poster session
(Presiders: Adi Perelman and Naftali Lazarovitch, Ben-Gurion University of the Negev)

1. Nicolai Paul Koebernick, Faculty of Engineering and the Environment, University of Southampton, Southampton, United Kingdom

Root hair impact on soil structure formation in the rhizosphere

Plant roots produce hairs and mucilages that interact with soil to improve conditions for plant growth. By their nature, root hairs are small (3-50 μm), fragile and have limited longevity in soil. Very recently, root hair growth into soil was visualised in intact soil specimens using Synchrotron X-Ray CT imaging, and the purpose of this work was to explore the effect of root hairs on soil structure formation by comparing mutant plant lines of barley that had greatly reduced root hair growth against wild-type lines. Plants were grown to one week of age in specially constructed soil-filled chambers of 1-ml volume that allowed for the high resolution imaging that was required. For the wild-type plants, we had an additional wetting-drying treatment to investigate the effect of pore water fluctuations on structure development. Scanning was done with the I13 Beamline at the Diamond Light Source. Image analysis is currently underway to quantify the amount of root hairs and changes to the soil physical structure at the root soil interface. Changes in pore size distribution and connectivity at the root:soil interface, compared to surrounding soil, are being analysed, with the hypothesis that changes will be greater for the wild-type plants compared to the mutants without root hairs. We will also try to measure the penetration of root hairs into the surrounding soil as this affects the radial impact of roots on resource capture from soil. First assessments of the images show that root hairs and internal structures of the roots could be clearly visualised. Shoot heights were significantly greater ($P < 0.05$) for the root hair mutants compared to the wild-type, with no impact on shoot height from the watering treatment. The preparation of samples for scanning presented a challenge in this work, so we are exploring different packing methods to ensure that the starting soil physical properties are homogeneous and structureless.

2. Harini Rangarajan, Pennsylvania State University, State College, PA, USA

Multi-objective optimization of root systems using evolutionary algorithms: matching root systems and environments

Global agricultural productivity is limited by low nutrient availability. Selection of plants with optimal root architecture can improve nutrient acquisition. Root architecture is dependent on a number of traits (phenes). In order to exploit a root phene for crop improvement, it is necessary to map the fitness landscape against an array of factors, including soil resource acquisition in high and low input agrosystems, a range of soil environments and nutrient environments, contrasting complex nutrients, co-occurring nutrients and water stress, interactions with other phenes, and more. Collecting and evaluating root phenotypic data is laborious and expensive.

Such problems involving searches across a multidimensional search space, optimizing multiple conflicting objectives, have been addressed in various fields of study, ranging from aerospace engineering to gene expression profiling, through the use of multi-objective evolutionary algorithms (MOEAs). Exploration of the root phenotypic space by linking functional structural plant models to evolutionary optimization algorithms is a promising approach.

In this study, we demonstrate the application of an MOEA to find optimal root architectures for the acquisition of N and P by maize and common bean. The three-dimensional structural functional root architectural model, SimRoot, was linked to the BORG MOEA, and the optimization runs were evaluated for several generations of solutions to find the optimal root system in terms of biomass production, nutrient acquisition and root carbon costs.

Data mining and machine learning techniques enable the exploration and analysis of the resulting multivariate high-dimensional data. Visualizations for the pareto-optimal sets and optimal root systems are rendered using VIDEO and VTK.

We demonstrate that more than one optimal architectural phenotype exists for a given environment.

3. Hannah M. Schneider[1], Tobias Wojciechowski[1], Johannes A. Postma[1], Dagmar van Dusschoten[1], Jonathan P. Lynch[2]
1: Forschungszentrum Jülich, IBG-2, Jülich, Germany 2: The Pennsylvania State University, University Park, PA, USA

Root cortical senescence influences metabolic costs and radial water and nutrient transport in barley

Root cortical senescence (RCS) is a type of programmed cell death in the cortical cells of many Poaceae species. The functional implications of RCS formation are poorly understood, but studies suggest that RCS formation confers both benefits and costs. The objectives of this research were to test the hypotheses that: (1) genetic variation exists in RCS; (2) RCS reduces the metabolic cost of root tissue; and (3) RCS decreases radial water and nutrient transport. Using a Pitman chamber, radial water and nutrient transport were measured from excised roots of barley using stable and radioactive isotopes. Landraces had greater RCS formation than modern genotypes. Nitrogen- and phosphorus-deficient conditions increased the rate of RCS development in all lines. RCS decreased the metabolic cost of root tissue: RCS reduced root nitrogen content by 66%, phosphorus content by 63%, and respiration by 87% compared to root segments with no RCS of the same length. Older root segments with complete RCS had 90% less radial water transport, 92% less radial nitrate transport, and 84% less radial phosphorus transport compared to younger root segments with no RCS. RCS was associated with 30% greater aliphatic suberin content in the endodermis. RCS may be a useful adaptation to drought by reducing the metabolic costs of soil exploration. As RCS progresses, less metabolic resources need to be invested in cortical maintenance, which could permit greater resource allocation to the growth of shoots, other roots, and reproduction. Reduced hydraulic conductivity induced by RCS may also be advantageous under drought conditions by preventing desiccation of the root tip and surrounding soil. These proposed merits of RCS under edaphic stress need further investigation under field conditions.

4. Gaochao Cai, Jülich Research Center, Institute of Bio- and Geosciences (IBG-3), Germany.

Parameterization of root water uptake models that consider dynamic root distributions and compensation

The estimation of crop water use and requirements is vital for efficient water management and crop production in agronomy. Modelling the distribution of water in the root zone and of root water uptake (RWU) offers the opportunity to make predictions of crop water use resulting from the interaction of the soil water balance and drought stress. Root distribution and its change over time play key roles but are often simplified in RWU models. Describing RWU from a profile with a vertical gradient in water content and root density poses another challenge.

Time series of the root distribution of winter wheat were obtained from rhizotubes installed horizontally at depths of 0.1, 0.2, 0.4, 0.6, 0.8 and 1.2 m. They served as inputs to two RWU models implemented in Hydrus 1-D: (i) the coupled Feddes et al. (1978)-Jarvis (1989) model, which describes RWU and compensation from ad hoc concepts, and (ii) the Couvreur et al. (2012) model, which derives RWU and compensation from a physical description of water flow in the coupled soil-plant continuum. RWU properties and soil hydraulic parameters were optimized by inverse modelling using (i) measured time series of soil water contents and water potentials for the objective function, and (ii) the time series of potential evapotranspiration estimated from the leaf area index and measured rainfall as boundary conditions. The results showed that both root water uptake models could describe the measured soil water contents and predicted similar actual transpiration rates. The parameters of the model could be identified and were constrained by the observations. Root water uptake compensation had to be considered in order to describe the observed water content measurements.

5. Nathaniel Alexander Bogie, University of California, Merced, Merced, CA, USA

Effect of native shrubs on water retention, hydraulic conductivity, and soil surface evaporation in the peanut basin, Senegal

A changing climate, along with human and animal population pressures, can have devastating effects on crop yields and food security in the Sudano-Sahelian region. Significant differences in crop success have been observed in peanut and millet grown in association with two native evergreen shrubs, *Piliostigma reticulatum* and *Guiera senegalensis,* at the sites of Nioro du Rip, Senegal and Keur Matar, Senegal, respectively. We investigated how these shrubs can affect soil physical properties in sites where the plants have been present for over 50 years, as well as in sites where the plants were introduced within the last 15 years. We measured water retention using the dual tensiometer evaporation technique. We then measured the dry-end water retention using a chilled mirror dewpoint potentiometer. We found significant differences in water retention and hydraulic conductivity between the *P. reticulatum* sites and the *G. senegalensis* sites. We did not find significant differences in water retention between the shrub-associated and the non-associated soils at either site; however, the soils from the 10-cm depth beneath the shrub, compared to those outside of the influence of the shrub canopy, had lower evaporation rates under the same environmental conditions in the laboratory. This was corroborated by the lower surface hydraulic conductivity that was measured using mini-disk tension infiltrometers at -2 cm of suction. If these shrubs create lower hydraulic conductivity in the surface soil, they may help to increase the residence time of water in the shallow soil, which is critical to the establishment of seedlings during the drought-prone early season. Management of these shrubs in an agroforestry system, already performed by many farmers, is applicable across wide swaths of the Sahel with the potential to significantly improve crop yields in a chronically food insecure area.

6. Jessie Godfrey, University of California-Davis, Davis, CA, USA

Salt exclusion and dilution through dispersal in pistachio

Objectives: Quantify Na (and Cl) exclusion at the roots by several rootstocks. Quantify xylem retrieval of Na (and Cl) along the transpiration stream of several rootstocks and the commercially prevalent scion. Understand tradeoffs between salts (including essential nutrients) at sites of uptake, as well as at sites of xylem retrieval. Propose mechanisms.

Methods: Coarse sand in 10 gallon pots. Daily leaching to maintain drainage EC no more than 2 dS/m above irrigation water EC. Three salt treatments: 0 mM NaCl, 50 mM NaCl (+25 mM CaCl), and 100 mM NaCl (+50 mM CaCl). After growing season, collect tissue samples and extract xylem sap at several heights. Digestion of non-sap samples, then analysis using an Na-specific electrode or ICPMS (Na, Ca, Mg, K, Cl) and stable isotopes (N).

Results: Pistachio trees exposed to salinity exclude a large percentage (on average 85% and 72% in our 100-mM and 50-mM treatments) of any sodium in soil water completely, and extract much of the sodium not excluded along their transpiration streams, sequestering it into root, stem and lower leaf tissues. Additionally, although exclusion is most effective at high concentrations of applied sodium, further dilution through dispersal offers no protection to photosynthesizing and growing leaves at concentrations so high that they overwhelm a tree's retrieval system. Non-sodium results forthcoming.

Interpretation: The maximum exclusion values and extraction rates for harmful salts are potential screening targets for breeders. Salt analyses of stem tissues collected at multiple heights also offer a potential new tool for assessing salinity's infringement upon a tree's safety margin as the retrieval systems of trees that continue to exhibit tissue concentration declines up the stem are operational and offering some degree of protection to photosynthesizing leaves.

*7. Yong Zhou***,** Texas A&M University, College Station, TX, USA

Landscape-scale spatial patterns of root distribution along the soil profile: linking aboveground plant communities to belowground biogeochemical cycling

Objectives: Quantifying landscape-scale spatial patterns of root distribution along the soil profile based on spatially specific soil samples to a depth of 1.2 m, and relating these patterns to aboveground vegetation patterns and belowground soil C and N storage patterns.

Methods: A 160 m × 100 m plot divided into 10 m × 10 m grid cells was established in a subtropical savanna in which vegetation is characterized by a two-phase pattern consisting of discrete woody patches embedded within a grassland matrix dominated by C_4 species. In each cell, two random points were selected to sample soils to a depth of 1.2 m. Each soil core was divided into six depth increments. Root biomass, soil organic C and total N were determined. Ordinary kriging and other spatial analyses were used to map, quantify, and relate spatial patterns of soil variables.

Results: Kriged maps showed that root biomass was highest at the center of the woody patches, decreasing towards the canopy edges of the woody patches, and reaching the lowest values within the grassland matrix across all soil depths. However, the spatial heterogeneity of root biomass distribution across this landscape differed significantly among soil depths. Kriged maps of soil organic C and N storage presented similar spatial patterns across all soil depths.

Interpretation: Plant life form (woody patches vs. grasslands) determined the horizontal and vertical distribution of roots across this subtropical savanna landscape. Roots, as a predominant source for soil organic matter input, regulate the spatial patterns of soil organic C and N storage along the soil profile. Quantifying spatial patterns of root distribution along the soil profile provides a potential way to link aboveground plant communities to belowground biogeochemical cycling across the landscape-scale.

8. Dr. Sarah Garre, Department Biosystem Engineering (BIOSE), University of Liege, Gembloux, BELGIUM

Impact of tillage practices on soil moisture dynamics in a temperate climate: potential of 3-D electrical resistivity tomography (ERT)

Adapted agricultural soil management practices can enhance soil health by providing improved aggregate stability and soil structural quality. Hence water infiltration may be facilitated and plant water availability increased. In this study, we aim at quantifying the effect of tillage practices on the water dynamics in a loamy soil under a temperate climate (Gembloux, Belgium). Therefore, we evaluated the ability of electrical resistivity tomography to estimate the water content at the plot scale and under complex field conditions, including varying pore water conductivity, rainfall, crop water uptake, root growth, and temperature, as well as changing soil structure due to tillage practices.

During the summer of 2015, we studied four different treatments: conventional spring and winter tillage, strip tillage and bare soil. We used ERT to estimate the spatio-temporal distribution of soil moisture. In each of the plots, two time-domain reflectometry (TDR) probes and two suction cups were installed. A calibration trench was constructed with four electrodes, one TDR probe and one temperature sensor at four different depths. We quantified changes of porosity over the growing season using X-ray tomography. Combining these data, we investigated and quantified the effect of simultaneously changing pore water conductivity, soil porosity, soil temperature, and soil moisture on the effectiveness of time-lapse ER measurements as a proxy for soil moisture changes under different tillage practices.

9. Dr. Fabio J. K. Mallmann, Ministry of Education of Brazil, Brasilia, DF, Brazil / University of California Riverside, Riverside, CA, USA

Effects of plant roots on modelling the vertical transport of copper and zinc in a clayey Oxisol contaminated by long-term pig slurry amendments

Objective*:* To numerically evaluate the effect of root growth and root water uptake on the vertical transport of Zn and Cu in a clayey Oxisol cultivated under annual cropping in a no-tillage system and contaminated by successive pig slurry (PS) applications.

Methods*:* We obtained soil, crop, manure and atmospheric data from an 11-year-long field experiment with increasing PS doses. Daily evapotranspiration was calculated according to the Penman-Monteith equation. Hydrus-1D was used to simulate the Zn and Cu vertical transport in the PS-amended soil profiles for two different PS doses (50 and 200 m^3 $ha^{-1}year^{-1}$) during 4063 days (experiment duration). First, a modeling approach (a two-site sorption model, without considering effects of roots) previously validated for an Alfisol was tested. Second, root water uptake (the Feddes absorption model) and growth of crops cultivated during the experiment were additionally considered.

Results*:* The correspondence between concentrations simulated by the Hydrus-1D model and those measured in the field improved for the second approach, leading to the validation of the transport model for Zn. Although the simulated results for Cu were not as good as for Zn, considering the effects of roots resulted in a reduced Cu accumulation in the surface layer, which was overestimated by the first modeling approach.

Interpretation*:* The first modeling approach, in which all water on the soil surface was lost due to evaporation ($ET_p=E_p$), produced high surface concentrations of Cu and Zn. The second modeling approach, which considered root processes ($ET_p=E_p+T_p$), allowed a fraction of water from the most contaminated surface layer to infiltrate downward into the root zone to supply the transpiration process. As a result, this downward movement helped redistribute dissolved Zn and Cu into a deeper layer.

10. Laura Jane Cooper, University of Southampton, Southampton, United Kingdom

Image-based modelling of two-fluid flow in soil

Objectives: Proof of concept study to model the flow of two fluids through a soil sample with geometry visualised using x-ray CT. The flow of two fluids will be modelled using the Cahn-Hilliard-Stokes phase field equations and upscaled using the theory of Daly and Roose (2015).

Methods: A sample of partially saturated soil was imaged using high resolution x-ray CT allowing for a non-destructive three-dimensional reconstruction of the soil particle geometry. The air phase, water phase and soil particles were segmented separately by applying threshold values to the grayscales. These were used to determine the initial geometric position of the phases and the soil for the numerical model. The computational mesh was generated using ScanIP. The soil particles were modelled as a fixed with a no-slip boundary condition for both fluids. Using the Cahn-Hilliard-Stokes model, the saturation level of the soil was increased and decreased in 1% increments from 0% to 100% saturation in order to calculate water release curves and hydraulic conductivity.

Interpretation: The method described above allowed for the prediction of the water release hysteresis loops that originate from soil pore structure. The computational method provided a step change in efficacy for estimating water release curves for specific soil samples and allowed us to investigate the effect of microscopic soil properties on the macroscopic behaviour. The next step will be to incorporate physical changes in pore water chemistry driven by exudation (surface tension, viscosity, contact angle) to understand local impacts on water retention. Eventually, hydromechanical data will be incorporated into model changes in soil physical structure over a defined time period.

11. Adi Perelman (Ben-Gurion University, Israel), Helena Jorda Guerra, Jan Vanderborght, Andreas Pohlmeier, Shimon Rachmilevitch and Naftali Lazarovitch

Plant water-uptake effects on salt distribution at the root-soil interface

In recent years, increased salinization of soils, along with the depletion of available water, has become a major threat for agriculture. The rhizosphere plays an important role in connecting processes at the soil-plant-atmosphere interface. A better understanding of these connections and their mutual influences can help in improving crop yield. New technologies provide better tools with which to study root structure and function in non-destructive ways. These techniques also provide a finer resolution regarding processes occurring where the roots meet the soil, e.g., water uptake and salt accumulation. The initial results from rhizoslides (capillary paper growth systems) show that the salt concentration gradient decreased with distance from the root, compared with the bulk that remained more stable. Also, differences in Na^+ accumulation around roots were noticed under different transpiration rates. In addition, images of roots were taken on a daily basis and will be used to incorporate the root growth rate and architecture into a numerical model. At the microscopic scale, magnetic resonance imaging (MRI) will be implemented to observe root structures, water content and sodium concentration distributions around single roots. An initial image of the tomato roots was taken as preparation for monitoring Na^+ accumulation around the roots. Data will be used to calibrate a model that is expected to predict root water uptake in saline soils for different climatic conditions and different soil water availabilities. Sensitivity analyses from a simulation study with this detailed model for different soil salinities, irrigation regimes and weather scenarios will be presented.

12. M.B. Kirkham, A. Alghamdi[1], 12. M.B. Kirkham [1], D.R. Presley[1], G. Hettiarachchi[1], and L. Murray[2]
[1] Department of Agronomy, Kansas State University, Manhattan, Kansas 66506
[2] Department of Statistics, Kansas State University, Manhattan, Kansas 66506

Root uptake of heavy metals from an abandoned mine site

Abandoned mine sites in the U.S.A. have left a legacy of environmental contamination. The lead (Pb) and zinc (Zn) mines in the Tri-State Mining District of southeast Kansas, southwest Missouri, and northeast Oklahoma are such mines. This district includes Galena, Kansas, where mines were operational from 1871 until the 1970s, when they closed. The waste materials around the mines are highly polluted with Pb, Zn, and cadmium (Cd), which often co-occurs geologically with Zn. In May 2006, researchers at Kansas State University added amendments to two sites at Galena, to see if they would decrease the bioavailability of the heavy metals in the mine waste materials. One site, called Site A, was about 10 km outside of the town of Galena and in a barren, uninhabited area. The other site, Site B, was in Galena, and houses were near it. At each site, seven treatments with three replications (21 plots at each site) were established, as follows: (1) non-amended control plot; (2) a low compost treatment of 45 Mg/ha; (3) a high compost treatment of 269 Mg/ha; (4) low compost (45 Mg/ha) + lime as $Ca(OH)_2$ (11.2 Mg/ha); (5) high compost (269 Mg/ha) + lime as $Ca(OH)_2$ (11.2 Mg/ha); (6) low compost (45 Mg/ha) + lime as $Ca(OH)_2$ (11.2 Mg/ha) + bentonite applied at 50 g bentonite/kg compost; and (7) high compost (269 Mg/ha) + lime applied as $Ca(OH)_2$ (11.2 Mg/ha) + bentonite applied at 50 g bentonite/kg compost. After the original experiment ended in 2007, the plots remained idle. In November 2014, 8.5 years after the addition of the amendments, the soil from the plots was sampled and brought back to Manhattan, Kansas, where a greenhouse study was established to determine the effect of biosolids (sewage sludge) on the bioavailability of the heavy metals.

The liquid aerobically digested biosolids came from the Manhattan, Kansas Wastewater Treatment Plant. Before planting, half of the pots each received 1000 mL of the liquid sludge. On 28 January 2015, 20 seeds of the forage crop sudex, a sorghum-sudangrass hybrid [*Sorghum bicolor* (L.) Moench x *S. sudanese* (P.) Staph.], were planted in 84 pots (each 22 cm diam.; 22 cm height) with drainage holes. The experiment was a replicated, randomized complete block design with 84 pots (2 sites; 7 original treatments; 3 replications; and 2 new treatments, i.e., with and without biosolids). On 18 Feb. 2015, plants were thinned to 10 plants per pot. Pots were kept well-watered during the experiment by monitoring the soil water content with a hand-held moisture meter. Plants were harvested on 18-19 May 2015 by cutting the culms just above the soil surface. Grain was removed, if a plant had produced grain. Leaves and culms were combined and labelled “shoots.” Roots were washed free of the waste material. The roots, shoots, and grain were digested using a nitric-perchloric acid digest and analyzed for heavy metals using inductively coupled plasma-atomic emission spectroscopy (ICP-ES) by the Soil Testing Laboratory at Kansas State University. Here we report the results for Pb, Zn, and Cd.

Roots at both Site A and Site B were highly contaminated with Pb, Zn, and Cd, but the contamination was less at Site B than at Site A. Because differences in concentrations of Pb, Zn, and Cd in the roots were not evident among the original seven treatments, they were averaged together. Concentrations (mean $\pm$ standard error) of Pb in the roots at Site A with and without biosolids were 1196.8 $\pm$ 77.1 and 1504.7 $\pm$ 112.3 mg/kg, respectively; for Site B they were 585.0 $\pm$ 22.7 and 715.1 $\pm$ 25.5 mg/kg, respectively. Concentrations of Zn in the roots at Site A with and without biosolids were 7771.7 $\pm$ 692.4 and 5174.8 $\pm$ 448.7 mg/kg, respectively; for

Site B they were 3230.7 ± 404.6 and 5045.6 ± 774.7 mg/kg, respectively. Concentrations of Cd in the roots at Site A with and without biosolids were 42.6 ± 3.4 and 56.4 ± 3.4 mg/kg, respectively; for Site B they were 18.7 ± 1.8 and 42.0 ± 8.6 mg/kg, respectively. Except for Zn at Site A, the biosolids reduced the heavy metal concentrations in the roots. The heavy metals must have been bound to the biosolids, which made them less available for root uptake.

Concentrations of the heavy metals in the shoots were less than in the roots, and, except for Zn in the shoots at Site A, shoots grown with biosolids had lower concentrations of the heavy metals than shoots grown without biosolids. Concentrations (mean ± SE) of Pb in the shoots at Site A with and without biosolids were 59.7 ± 11.2 and 163.0 ± 18.5 mg/kg, respectively; for Site B they were 22.2 ± 4.4 and 121.0 ± 26.0 mg/kg, respectively. Concentrations of Zn in the shoots at Site A with and without biosolids were 2307.3 ± 310.4 and 1791.9 ± 97.8 mg/kg, respectively; for Site B they were 711.5 ± 147.0 and 1117.9 ± 173.3 mg/kg, respectively. Concentrations of Cd in the shoots at Site A with and without biosolids were 12.1 ± 1.5 mg/kg and 22.1 ± 1.3, respectively; for Site B, they were 6.6 ± 1.2 mg/kg and 10.5 ± 1.2 mg/kg, respectively.

Only the plants grown with biosolids produced grain. Concentrations (mean ± SE) of Pb in grain at Site A and Site B were 3.8 ± 1.0 and 1.8 ± 0.3, respectively. Concentrations of Zn in grain at Site A and Site B were 116.4 ± 8.4 and 57.0 ± 2.6, respectively. Concentrations of Cd in grain at Site A and Site B were 2.2 ± 0.1 and 0.7 ± 0.2, respectively. Plants grown in pots with the waste material from the high compost and lime treatment at Site B produced the most grain.

Even though the biosolids reduced the uptake of the heavy metals into the shoots, they were still highly contaminated with Pb, Zn, and Cd. Maximum levels of Pb, Zn, and Cd in plants grown in non-contaminated areas are 5.0, 150, and 0.2 mg/kg, respectively. However, in the grain, only Cd was elevated above normal levels. The results showed that biosolids reduced uptake of Pb, Zn, and Cd and that, even though large amounts of Pb, Zn, and Cd accumulated in the roots, Pb and Zn concentrations in the grain were normal. The use of biosolids appears to be a promising method to reduce the bioavailability of heavy metals at contaminated mine sites.

13. Shmulik Friedman and Boris Naftaliev, Institute of Soil, Water and Environmental Sciences, The Volcani Center, Agricultural Research Organization, P.O. Box 6, Bet Dagan 50250, Israel

Factors affecting the aeration status of the root zones in drip-irrigated orchards

We extensively surveyed the soil aeration status in the root zone of 35 commercial, drip-irrigated Israeli orchards in order to evaluate the extent and severity of soil hypoxia in drip-irrigated orchards. The survey involved measuring soil gaseous O_2 concentrations at depths of 0 to 60 cm, 20 cm to the side of the emitter. Oxygen concentrations at active root depths were usually higher than 15% (vs. 21% in the atmosphere) and decreased approximately linearly with increasing depth. During the cold, rainy winter, the soil O_2 concentrations were usually higher than in the warm irrigation season, but after heavy rain, they usually dropped for a few days. Low O_2 concentrations were mostly found in intensively irrigated clayey soils. The negative gradients of O_2 concentration vs. depth were highly correlated with soil water content which, in turn, was highly correlated with the soil clay content. Thus, the concentration gradients were also higher in orchards irrigated with a single drip line per tree row than in those with two lines per row. The O_2 concentrations decreased with increasing temperature. In a few sites, those in plots irrigated with recycled effluent water were similar to or slightly lower than those in plots irrigated with fresh water at similar rates. Within each irrigation cycle, the O_2 concentrations decreased after water application and increased as the soil dried. Several observations showed that O_2 concentrations near mature trees were lower than those near young trees or in uncultivated soil. A rough evaluation of the diffusive vertical O_2 flux, averaged over all orchards and based on the mean O_2 concentration gradient and on the mean O_2 diffusion coefficient, yielded a value of 15 g m^{-2} day^{-1}, which is consistent with reported respiration rates of cultivated soils at 25 °C. It is likely that in some circumstances, this O_2 diffusion rate may be a limiting factor with regard to root respiration, photosynthesis, water and nutrient uptakes, and plant growth and yield, especially under intensive irrigation and fertigation and at elevated soil temperatures.

14. Alon Ben-Gal, ARO, Volcani Center, Israel

Applied physics for water and nutrient use efficiency: ultra-high frequency application and salinity and their effects on root uptake

Water and nutrient use efficiencies are increased under drip irrigation as zones of relatively high water content and high concentrations of minerals in solution are maintained and availability for root uptake is maximized. Potentially, due to this relatively high availability, water and nutrient application rates under drip irrigation can be reduced without negatively affecting crop growth and yield. Indeed, studies show benefits in water and/or nutrient savings as drip irrigation frequency increases, from intervals of weeks or days between irrigation events, as practiced under other application methods, to daily or multiple applications per day, made possible with pressurized drip systems that can be explained by models of water and/or nutrient uptake.

Can high availability be infinitely beneficial or is there a limit to potential uptake efficiency by roots in agricultural systems? What about low water quality? When salt leaching is required, just how do ultra-high frequencies or ultra-low flow rates stand up? Data from the literature, from experiments and from modelling of crops, including grapevines, bell peppers, radishes, melons, and corn, are introduced to address these questions.

The results indicate that, with good quality water and most soils, great benefits occur as applications increase to daily and even to 4-8 times per day but that little, if any, additional benefit is found as irrigation regimes reach more than several applications per day or start lasting throughout most of the day. With water containing problematic concentrations of dissolved salts, the highest frequencies and lowest flow rates subtly, but consistently, indicate a lower capability for leaching.

15. Tamir Klein[1,2], Rolf T. W. Siegwolf[3] & Christian Körner[1]
[1] Institute of Botany, University of Basel, Schönbeinstrasse 6, 4056 Basel, Switzerland

[2] Institute of Soil, Water and Environmental Sciences, ARO Volcani Center, Beit Dagan 50250, Israel
[3] Laboratory of Atmospheric Chemistry, Paul Scherrer Institute, PSI, 5323 Villigen, Switzerland

Belowground carbon trade among tall forest trees

Just imagine if one tree could hand over large quantities of carbon to another tree. How would that change our thinking about the carbon relations of forests, the single biggest biological C reservoir on earth? If such a tree-to-tree C shuttle existed, it would require a demand-supply gradient and a pipeline. Here we show that exactly this unthinkable scenario does occur in the overlapping root spheres of tall trees in a mixed temperate forest. Using canopy-scale stable carbon isotope labelling applied from a construction crane, we demonstrate that carbon assimilated by spruce is traded over to neighbouring beech, larch, and pine in amounts so large that fine roots almost equilibrate the carbon source signature. The isotope mixing ratio indicated that the interspecific transfer accounted for 40% of the fine root carbon, which is ca. 280 kg ha^{-1} a^{-1}. This is the first forest-scale evidence of a large flux of carbon between mature trees from evolutionary distant taxa. Carbon transfer most likely occurred through common ectomycorrhiza networks, which also exhibited the labelled carbon signal. These observations indicate that while competition for resources (e.g., light, water, nutrients) is often considered the dominant tree-tree interaction in a forest, trees actually interact in more complex pathways, including a massive carbon exchange.

16. Andrew M. Ireson (1), Amber Peterson (1), Warren Helgason(1), 1. Global Institute for Water Security, University of Saskatchewan, Canada

Estimation of field-scale root zone soil moisture

For most practical applications, soil moisture estimates are needed at the field scale, integrated over the root zone. We present here results from a field study in a pasture site in Saskatchewan, Canada. We combine observations of point-scale soil moisture content from an array of neutron probes with continuous field-scale shallow soil moisture content observations from the COSMOS instrument. The neutron probe data provide insights into the spatial variability of soil moisture processes, which is highly significant at this site. In particular, we find that the field comprises both non-participating profiles, in which infiltration and changes in storage and drainage are minimal, and dynamic profiles, in which these processes are highly dynamic. This strongly affects the relationship between the spatial mean and the standard deviation of moisture content, with important implications for the upscaling of point-scale observations to the field scale. The COSMOS performs well, but only captures changes in water content to a depth of around 20 cm, meaning that upscaling with depth is required to produce a field-scale, root-zone-integrated estimation of soil moisture content. We compare three upscaling approaches.

17. Helena Jorda Guerra (Katholieke Universiteit Leuven, Belgium), Adi Perelman, Naftali Lazarovitch and Jan Vanderborght

Linking the soil-root interface and bulk salinities to improve macroscopic modeling of osmotic stress effects on root water uptake

Current soil-hydrological models predict the effect of salt stress on macroscopic root water uptake by using so-called transpiration reduction functions. Knowledge of the relationship between the soil-root interface and bulk soil osmotic potentials throughout a growing season is essential for the development of such macroscopic stress functions since bulk salinity is used at the macroscopic scale, but it is salinity at the soil-root interface that determines the actual root water uptake.
Simulation experiments were conducted for a range of atmospheric conditions, irrigation water quality and scheduling using a 3-D physically based model that resolves flow and transport to individual root segments and that couples flow in the soil and root system. The effect of salt concentrations on root water uptake is accounted for by including osmotic water potential gradients between the solution at the soil-root interface and the root xylem sap in the hydraulic gradient between the soil and root. Simulation experiments were performed in a soil volume around a single root segment. In addition, the same model was used to reproduce rhizoslide (capillary paper growth systems) experiments performed under two transpiration regimes and different salinities. Simulations performed under constant irrigation showed weak osmotic potential gradients between the soil-root interface and the bulk soil. Water uptake was more sensitive to osmotic stress under a large transpiration rate, a high salinity level in the irrigation water, a small root length density and a low irrigation rate. Further analysis of the results shows how the gradient develops under transient conditions and how it affects root water uptake. Finally, we validated the model assumptions by reproducing the salinity gradients observed experimentally in the rhizoslides.

18. D. van Dusschoten, J. Kochs, V.A. Sydoruk, D. Pflugfelder and J.A. Postma
IBG-2, Forschungszentrum Jülich, Germany

Correlating root length densities with vertical soil water depletion profiles

Plant roots do not only affect the local soil water content; by means of flow in the soil, water concentration changes extend well beyond the root zone. This means that a complete assessment of the water profile within a plant container is required. Additionally, a time course of water concentration, especially due to the day-night rhythm of plant transpiration, should be useful. We developed a capacitive soil water sensor that can slide along the outside of a plastic cylinder containing the soil with plant roots. In this manner, 1-D water content profiles over the whole length of the container could be obtained. Calibrated sensors showed a good linear response over 0 to 20% soil water content. Measurement noise was at 0.1% water content. Using an r.f. switch, in combination with a vector network analyzer, four containers could be measured continuously and automatically. To correlate the soil water and its uptake with plant root lengths, 3-D root maps were acquired using MRI.
Four maize and bean plants were grown in 50-cm-long PVC-pipes (8 cm i.d.) and filled with mineral soil optimized for MRI usage. The highest water depletion occurred near the top and near the bottom, with the highest root density and the smallest water potential, respectively. A clear night-day oscillation could be recognized at the top; this pattern was weak to non-existent at the bottom. At later stages, day-night oscillations occurred everywhere, and the soil water depletion patterns showed a significant correlation with the root length density profiles.

The proposed sliding soil water sensor yields high quality data on spatiotemporal soil water profiles that is useful for studying differences in plant water uptake depending on environmental settings and plant type. This is especially true when combined with MRI root images.

19. Tamir Kamai (ARO, Volcani Center, Israel), Gerard J. Kluitenberg, Jan W. Hopmans, and John H. Knight

A perfect-conductor approach for the heat-pulse method

The heat-pulse method is attractive for measurements in rooting zones because multiple soil-water properties can be determined collectively at similar temporal and spatial scales, providing the high-resolution data that are required for quantifying related processes. We present advances in the method for sensors with cylindrical probes that have relatively large diameters and high thermal conductivity, so they can be approximated as perfect conductors. The heat-pulse method involves measuring the temperature rise at a known distance from a pulse heat source and analyzing the temperature data with a heat transfer model. The fitting of modeled to measured temperature data allows for estimation of the soil thermal properties: thermal conductivity, heat capacity, thermal diffusivity, and heat-pulse velocity. Volumetric water content is obtained from the estimated volumetric heat capacity, provided that the specific heat of the solids and the soil bulk density are known. Furthermore, water flux density can be obtained via the heat pulse velocity. In heat-pulse sensors with probes that are constructed from thick-walled stainless-steel tubing and whose diameter is large relative to the distance between the heater and temperature probe, the probes may be treated as perfect conductors. A perfect conductor model accounts for the finite radius and heat capacity of the probe, but approximates its thermal conductivity as infinite, assuming that the thermal conductivity of the probe is significantly higher than that of the soil. The use of a perfect conductor model for the single-probe heat-pulse method is not new. We present results of a rigid dual-probe heat-pulse (R-DPHP) sensor in combination with the identical-cylindrical perfect-conductors (ICPC) model. The rigid probes of this sensor are about five times more resistant to deflection than the probes that are commonly used for heat-pulse sensors, allowing for smaller flexing of the probes during sensor installation. Results show a root mean square error of 1.4% volumetric water content and elimination of the measurement bias typically encountered with DPHP measurements. We further elaborate on this methodology by analyzing errors that may arise from contact resistance and interactions between probes, and from the finite length of the probes. Finally, we present the preliminary results of a three-probe heat-pulse sensor with large-diameter probes for water-flux-density estimations.

20. Jennifer Pett-Ridge[1], Shengjing Shi [2,3], Erin Nuccio[1], Donald J. Herman[2,4], Marco Keiluweit[1,5,6], Zhili He[3], Liyou Wu[3], Peter Nico[4], Markus Kleber[6], Eoin Brodie[4], Jizhong Zhou[3,4], and Mary K. Firestone[2]
[1] Lawrence Livermore National Lab, Livermore, CA, pettridge2@llnl.gov
[2] UC Berkeley, Berkeley, CA
[3] University of Oklahoma, Norman, OK
[4] Lawrence Berkeley National Laboratory, Berkeley, CA

[5] U. Mass Amherst, Amherst, MA
[6] Oregon State University, Corvallis, OR

Carbon transformations in the rhizosphere: the critical role of microbial functional capacity

Carbon cycling in the rhizosphere is a nexus of biophysical interactions between plant roots, microorganisms, and the soil organo-mineral matrix. Although plant "priming" of decomposition is well-studied, it is not known how plant effects on the molecular ecology of microbial decomposers translate into altered rates of native organic matter breakdown. We examined the effects of live, dead and synthetic roots on rhizosphere decomposition in a grassland soil and quantified multiple genetic characteristics of relevant bacterial and fungal communities. We found that certain exudates, particularly oxalic acid, cause a net loss of soil carbon by liberating organic compounds from protective associations with minerals. In contrast, the presence of live roots consistently suppressed rates of 13C-labeled root litter decomposition and significantly altered the abundance, composition and functional potential of microbial communities (assessed by both metagenomic and transcriptome sequencing). Plant-influenced soils had relatively more genes involved in low molecular weight compound degradation (e.g. polysaccharides); unplanted soil microbes had more macromolecule degradation genes. Higher abundances of proV and proW genes (glycine betaine transport) in planted soils suggest microbes experience more severe water stress in planted soils. RNA-seq and stable isotope probing analysis showed that living roots in the presence of decaying root material had differential effects on soil food webs and organisms participating in the co-metabolism of exudates and decaying biomass. A quantitative model based on our data indicates that microbial functional potential is the primary factor driving rhizosphere litter decomposition and that microbial functional capacities differ in rhizosphere versus bulk soils.

21. Ido Regev, Ben-Gurion University of the Negev, Israel

Root system development as a stochastic growth process

It is well known that plant roots respond to the changing environment, including factors such as water content levels and nutrient availability. Roots ``know'' to orient themselves towards areas with higher water content and nutrient concentrations and away from salinity and other roots. Here we study the behavior of the root system as a stochastic growth process in which the tip of the root follows the maximal gradient in the field lines (the principle of local symmetry). We also allow for the branching of roots using a bifurcation rule and characterize the fractal dimension of the emerging pattern, which allows for a comparison with typical root architectures.

22. Amar Pal Singh[1], Yulia Fridman[1], Lilach Friedlander-Shani[1], Danuse Tarkowska[2], Miroslav Strnad[2], and Sigal Savaldi-Goldstein[1]

1. Faculty of Biology, Technion-Israel Institute of Technology, Haifa 3200003, Israel.
2. Laboratory of Growth Regulators, Institute of Experimental Botany ASCR and Palacký University, 78371 Olomouc, Czech Republic.

Activity of the brassinosteroid transcription factors BZR1/ BES1 blocks developmental reprogramming in response to low phosphate availability

Plants feature remarkable developmental plasticity, enabling them to respond to and cope with environmental cues, such as limited availability of phosphate, an essential macronutrient for all organisms. Under this condition, Arabidopsis (Arabidopsis thaliana) roots undergo striking morphological changes, including exhaustion of the primary meristem, impaired unidirectional cell expansion, and elevated density of lateral roots, resulting in shallow root architecture. Here, we show that the activity of two homologous brassinosteroid (BR) transcriptional effectors, BRASSINAZOLE RESISTANT1 (BZR1) and BRASSINOSTEROID INSENSITIVE1-ETHYL METHANESULFONATE-SUPPRESSOR1 (BES1)/BZR2, blocks these responses, consequently maintaining normal root development under low phosphate conditions without impacting phosphate homeostasis. We show that phosphate deprivation shifts the intracellular localization of BES1/BZR2 to yield a lower nucleus-to-cytoplasm ratio, whereas replenishing the phosphate supply reverses this ratio within hours. Phosphate deprivation reduces the expression levels of BR biosynthesis genes and the accumulation of the bioactive BR 28-norcastasterone. Correspondingly, low and high BR levels sensitize and desensitize root response to this adverse condition, respectively. Hence, we propose that the environmentally controlled developmental switch from deep to shallow root architecture involves reductions in BZR1 and BES1/BZR2 levels in the nucleus, which likely play key roles in plant adaptation to phosphate-deficient environments.

23. Effi Tripler[1], Ehud Zeelim[2] and Alon Ben-Gal[3], 1. Central and Northern Arava R&D, Israel; 2. The Hebrew University of Jerusalem, Faculty of Agriculture, Israel; 3. Environmental Physics and Irrigation, Agricultural Research Organization, Gilat Research Center, Israel

Laboratory validation of compensative root water uptake

Constraints on water resources and the environment necessitate more efficient use of water. Understanding the physical and physiological processes occurring at the soil-root hydrological continuum is key to efficient management. It is therefore important to better understand the governing processes controlling water uptake by roots, specifically under conditions of limited available water. Compensatory root water uptake theory implies that plants respond to nonuniform wetting patterns in their root zone by balancing reduced water uptake in a water-stressed part of the rhizosphere with greater uptake from regions with high water availability.
We constructed transparent PVC growing soil columns, filled with sandy soil, with an ability to alter the matric potential pattern by adjusting the water table level. The root zone of eggplant growing in one of the columns was split into two alternating soil matric regimes (wet and dry), and water uptake was measured from each of the compartments. Two additional non-split root columns (NSRC) were built. In each column, the lower boundary condition was equivalent to each of the two domains in the split-root column (SRC) system.
Measured water uptake in the SRC system showed high rates in the current wet compartment and minor uptake rates in the dry region, suggesting full compensation root water uptake. Plant water uptake rate was similar between the two NSRCs and

equivalent to the total measured rate in the SRC. We therefore suggest that preferential water uptake occurs in regions with relatively high water availability. The presented study successfully validated the Nimah and Hanks mechanistic root water uptake model, as modified by Dudly and Shani (2003), and demonstrated that under a relatively dry water regime, the plant's roots reduce their water potential in order to increase the root-soil gradient, thus maintaining an optimal water uptake.

24. N. Rudolph-Mohr[1], P. Vontobel[2], S. E. Oswald[1]
[1] Institute for Environmental and Earth Science, University of Potsdam, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany, [2] Paul Scherrer Institute, 5232 Villigen, Switzerland

Multi-imaging approach to studying the root-soil interface

Dynamic processes occurring at the soil-root interface crucially influence soil physical, chemical, and biological properties at the local scale around the roots, which are technically challenging to capture *in situ*. Combining fluorescence and neutron imaging, we developed and validated a new multi-imaging approach capable of simultaneously quantifying H_2O-, O_2-, and pH-distribution around living plant roots. The interrelated patterns of root growth and distribution in soil, root respiration, root exudation, and root water uptake can be studied non-destructively at high temporal and spatial resolutions.
Fluorescence sensor foils were attached at the inner-sides of thin boron-less glass containers, with one maize plant grown in each container. On days 11 and 25, we wetted the containers from the bottom and subsequently took time series of fluorescence and neutron images during day and night cycles.
The neutron radiographs made it possible to visualize and quantify the root system in association with the observed pH and oxygen patterns. The older part of the root system with a higher root length density was associated with a fast decrease in water content and a rapid change in oxygen concentration. The pH values around the roots located in areas with low soil water content were significantly lower than in the rest of the root system.
The results suggest that the combined imaging setup is able to map important biogeochemical parameters around living plants with a spatial resolution sufficiently high enough to relate patterns of the observed biogeochemical parameters to the root system.

25. Chen Fengxian and Gilboa Arye**,** French Associates Institute for Agriculture & Biotechnology of Drylands, The Jacob Blaustein Institutes for Desert Research (BIDR), Ben-Gurion University of the Negev, Sede Boqer Campus

Surface activity of root mucilage at the solid-liquid and liquid-air interfaces: the effect of the polysaccharide/lipid ratio

The rhizosphere can be defined as the volume of soil around living roots, which is influenced by root activity. The biological, chemical and physical conditions that prevail in the rhizosphere are significantly different from those of the bulk soil. Plant roots can release diverse organic materials into the rhizosphere, which may have different effects on its bio-chemo-physical activity. Among these exudates is the root mucilage, which can play a role in the maintenance of root–soil contact, in lubrication of the root tip, in protection of roots from desiccation and disease, in the stabilization of soil micro-aggregates and in the selective absorption and storage of ions. The surface activity of the root mucilage at the liquid-air interface is deduced from its surface tension depression relative to water, suggesting its amphiphilic nature. Consequently, as the rhizosphere dries out, hydrophobic functional groups may exhibit orientations at the solid-air interface, and thus, the wettability of the rhizosphere may temporarily decrease. The major fraction of the root mucilage comprises polysaccharides and, to a much lesser extent, amino acids, organic acids, and phospholipids. The most frequently detected polysaccharide and phospholipids in root mucilage are polygalacturonic acid (PGA) and phosphatidylcholine (PC), respectively. The latter is thought to be the main cause for the surface active nature of root mucilage. Nevertheless, the role and function of root mucilage in the rhizosphere are commonly studied based on a model root mucilage that includes only one component, in which the most common ones are PGA or PC (or lecithin). The main objective of this study was to quantify the effects of concentration and PGA/PC ratios on the wettability of a model rhizosphere soil and the surface tension of the model root mucilage at the liquid-air interface. The PGA/PC mixtures were measured for their surface tension using the Wilhelmy plate and the pendant drop methods. Soils with different particle size distributions were coated with the above solutions and measured for their initial advancing contact angle, using the capillary rise and sessile drop methods. The results of this study will be presented, and their implications for the wettability of the rhizosphere will be discussed.

26. Robert Heinse, University of Idaho, USA

Morphology of soil pipes created by root decay and combustion

Tree root materials that have been decaying in forest soils for some time can combust during forest fires and either create what we call soil pipes--large open networks in the soil--or at least connect such networks to the soil surface. These macropore pathways may result in saturation-threshold-driven preferential flow. Over a period of three years, we i) quantified the spatial distribution and physical characteristics of such soil pipes, ii) investigated soil pipe origin, and iii) examined the role of fire in pipe formation. We unsuccessfully used electrical resistivity tomography to study the in-situ distribution of soil pipes prior to and after a prescribed fire burn on steep forest hillslopes in northern Idaho underlain by a water-restricting horizon. However, subsequent excavation of three 6.12 x 6.12 m plots provided detailed documentation of the soil pipe diameter, direction, gradient and connectivity used to derive the morphologic attributes and distribution of soil pipes. The majority of soil pipes were attributed to decayed tree roots with a median depth of 0.32 m corresponding to the beginning of the restrictive soil horizon. The median path lengths for branched and non-branched soil pipes were 2.21 m and 0.89 m, respectively, with a median tortuosity of 1.23. Our findings indicate that tree root growth, influenced by slope gradient and root-limiting soil horizons followed by decay, determine soil pipe formation and distribution within these hillslopes, whereas fire and the combustion of roots and tree stumps contributed predominantly to connecting soil pipes to the surface. The large frequency and extent of soil pipes documented in this study suggest that estimations of water transport without consideration for these macropores are likely underestimated.

27. A. Pohlmeier

S. Haber-Pohlmeier*, A. Pohlmeier† and Jan Vanderborght†

* Institute of Technical and Macromolecular Chemistry, RWTH Aachen University
e-mail: haber-pohlmeier@itmc.rwth-aachen.de
† Institute for Bio- and Geosciences 3, Research Center Jülich, Germany
e-mail: a.pohlmeier@fz-juelich.de

Imaging of root water uptake by MRI in combination with tracer motion

Flow processes in natural porous media are often too slow to be monitored by direct flow imaging; therefore, the visualization of such fluxes is best performed by tracer tracking. While T1 reducing contrast agents are well known in medical diagnostics, their usefulness in natural porous media is not yet well explored. As pointed out in a preceding study [1], GdDTPA is the most convenient since it is very stable and does not adsorb at the soil matrix. Furthermore, its specific relaxivity in the liquid phase is sufficiently high to yield good contrast when used in a strongly T1 weighted pulse sequence. Here, we use a simple procedure for the quantification of the tracer concentration in saturated and unsaturated natural porous media, where the reduction of relaxation times by desaturation is compensated for by a reference measurement. The procedure is applied to examples from natural porous media, which are decisive bottlenecks in the water flow from the soil to the atmosphere: root water uptake and evaporation from topsoil.

While plant roots take up water from the surrounding soil, GdDTPA is first enriched in the neighborhood of some roots, indicating their activity. But the tracer is also enriched in the immediate, several mm thick layer around the root, the so-called rhizosphere, which appears dark in conventional MRI sequences. Although this layer has been frequently interpreted as a water depletion zone, the enrichment of GdDTPA there proves the high permeability for water and solutes.

References

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28. Dilia Kool, Joshua Heitman, Naftali Lazarovitch, Nurit Agam, Tom Sauer, Alon Ben-Gal

Evaluation of heat-pulse sensor to measure evaporation in a desert vineyard

The heat-pulse sensor soil heat balance method (HP-SHB) is used to calculate sub-surface evaporation (E) without interfering with root water uptake or requiring micro-climate data, making it uniquely suitable for continuous measurement below a canopy. The HP-SHB method has been successfully applied to evaluate E under controlled conditions in the laboratory, at bare soil sites and, more recently, beneath a corn canopy in a temperate climate. In this study, the method was applied in a drip-irrigated vineyard under extreme arid conditions. Results will be presented regarding sub-surface evaporation as a function of time after irrigation, time of day, and under different stages of vine canopy development. In addition, an in-situ calibration of thermistor offsets was developed and tested in the laboratory before and after field deployment, removing errors of up to 50% from *E* computations. The field assessment indicated that the HP-SHB method successfully monitored sub-surface *E* in the vineyard at several intervals during the season. As surface *E*, not measurable by the HP-SHB, dominates immediately following an irrigation event, high irrigation frequency limited the number of days in which HP-SHB measurements were relevant. Magnitudes of HP-SHB *E* were similar to pre-season eddy covariance measurements following a rain event, as well as to mid-season micro-lysimeter measurements. The high resolution data collection allowed the assessment of diurnal patterns of *E* and the time at which *E* shifted to the sub-surface.

29. Ido Nitsan and Shmulik Friedman, Institute of Soil, Water and Environmental Sciences, The Volcani Center, Agricultural Research Organization, P.O. Box 6, Bet Dagan 50250, Israel

On the effects of plant roots on soil hydraulic conductivity at saturation

Most literature studies comparing the hydraulic conductivities of bare and (natural or cultivated) plant-containing soils report higher hydraulic conductivities in soils containing plant roots. This is a bit surprising since at least living roots are expected to act as obstacles to soil water flow. In a series of column experiments, we measured the axial (vertical) hydraulic conductivity at saturation of sand columns with and without bell pepper plants at different stages of the plant's (shoot and) root system development. The hydraulic conductivities of the soils of the plant-containing columns were systematically lower during the plant development period. After cutting the shoots of the pepper plants, and continuing the irrigation of the columns with and without decaying plant roots, their hydraulic conductivities stabilized at similar values. An evaluation of the hydraulic conductivity reduction, based on the measured root system volumes, employing approximate mean field computations and describing the pepper roots as either randomly oriented or aligned along cylinders, resulted in a much more moderate decrease in the hydraulic conductivities, compared to the measured ones. This means that beyond their role as mechanical obstacles, living plant roots affect the soil hydraulic conductivity via other mechanisms.

30. Allen G. Hunt, Wright State University, USA

From soils to allometry

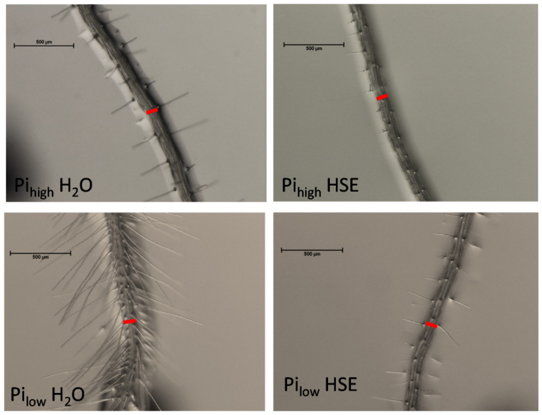
Soil-root interactions are key to many scientific issues in the earth's biosphere. We focus on changes in nutrient transport across this boundary with increasing spatial scales. An important precondition for understanding is predicting nutrient transport within the soil. For typical flow rates and pore size, and for such solutes as CO_2, HCO_3^- and NO_3^-, Peclet numbers exceed 1 at ca. 10 μm, which is the geometric mean of xylem diameters, and a critical pore diameter for flow under typical saturations through pores with diameters of 0.2 μm to 30 μm, the range preferred by plants. Since flow rates from percolation theory, about 1μ/s, are equal to typical flow rates in the subsurface, percolation scaling relationships then predict solute transport. Non-Gaussian transport results in a transport time that is superlinear in distance. This power-law predicts soil depths over time to 100 Ma; the temporal derivative of the depth gives the soil production function and a proxy for chemical weathering rates.

Transport times for mineral-sized sources, 10^6 yr for 10 m, are profoundly inhibiting for plants, but the most serious limitations are overcome by developing a dendritic root architecture to grow towards heterogeneously distributed nutrients. Dendritic root systems eliminate loops in flow paths, and the location of the necessary nutrients in the top decimeters of the soil allows the search to occur in two dimensions. Such topological constraints increase the efficiency of nutrient assimilation dramatically, so access of nutrients at 100 m requires only centuries. Nevertheless, the transport time is still superlinear in distance, a result that not only explains the diminution of tree growth with age, but also the discrepancy between predicted and observed tree diameter-height allometric scaling. The enormous contrast between biotic and abiotic solute transport results helps in understanding the distinct time scales of soil formation by chemical weathering and biological carbon fluxes from soil exploitation.

31. Ellen R. Graber[1*], Ludmilla Tsechansky[1], Einav Mayzlish-Gati[2], Rony Shema[2], and Hinanit Koltai[2]
[1]Institute of Soil, Water and Environmental Sciences, Agricultural Research Organization, Volcani Center, Israel; [2]Institute of Plant Sciences, Agricultural Research Organization, Volcani Center, Israel

Do organic chemicals that accompany biochar play a role in plant growth? A study of root hair development in *Arabidopsis* as affected by humic-like substances extracted from biochar

Organic chemicals that are not part of the polycondensed aromatic structure of biochar are numerous and consist of small molecules from classes such as hydroxyaldehydes, hydroxyketones, sugars and dehydrosugars, carboxylic acids, and phenolic compounds, and large molecules similar in structure and nature to humic substances. Few studies have directly examined the impact of biochar-borne organic chemicals on plant development, and the possible role of the humic-like substances fraction of biochar has been largely ignored, despite the fact that soil, compost, coal and peat-derived humic substances have been long thought to have positive effects on plant nutrition, seed germination, root initiation, and total plant biomass. Such effects have also been attributed to biochar. Biochar additions have likewise been reported to have positive impacts on phosphorus (P) availability to plants and to cause down-regulation of genes associated with P starvation. Humic substances from various sources also may induce partial relief from P starvation and, moreover, may cause an increase in total cell phosphate, ATP and glucose-6-phosphate levels. Our goal was to examine whether humic-like substances extracted from biochar (HSE) could affect plant responses to initial phosphate (Pi) concentration under Pi sufficient (Pi_{high}) and starvation (Pi_{low}) conditions. This was done by examining the impact of HSE in the growing media of *Arabidopsis* seedlings on root hair development (length and density) in sterile systems, and by evaluating whether nutrient complexation with HSE could account for observed differences. It was found that root hair length was significantly lower in HSE amended Pi_{high} growing media, and root hair density was significantly lower in both HSE amended Pi_{high} and Pi_{low} regimes as compared with non-amended treatments. The differences did not result from either primary (P source) or secondary (increased P availability) nutritional effects. The conclusion is that humic-like substances in biochar are capable of causing a change in plant perception of P nutrition, which may be another way that biochar impacts growing plants.



32. Patompong Saengwilai, Department of Biology, Faculty of Science, Mahidol University, Rama VI Road, Bangkok 10400 Thailand, Email: patompong.sae@mahidol.ac.th

Genetic variation for root architecture in response to drought stress of maize inbred lines in the Drought Tolerant Maize for Africa (DTMA) project.

Drought is a primary constraint to global maize production. Several lines of evidence indicate that root traits influence soil exploration and acquisition of water in drying soils. In this study, we explored the genetic variation of root architectural traits in 33 maize inbred lines from the Drought Tolerant Maize for Africa project (DTMA). The DTMA lines were grown under well-watered and drought conditions in a field in Nakhon Sawan Province, Thailand. We found that drought decreased the shoot dry weight and yield by 13.84% and 92.43%, respectively. Drought significantly affected nodal root formation by decreasing the number of crown roots by 21% and brace roots by 11%. In addition, the root growth angle became 5.5 degrees steeper under drought compared to well-watered conditions. Statistical analyses between 14 most drought tolerant and most sensitive lines indicated that the tolerant lines had 15% higher shoot mass, 40% higher photosynthetic rate and 80% greater yield than the sensitive lines under drought. A cluster analysis of maize lines based on root architectural traits under drought indicated that the majority of the tolerant lines had 7 degrees shallower root growth angle, 20% greater number of brace roots, 23% shorter lateral root length and 40% lower lateral root branching than those of the sensitive lines. Our results support a hypothetical ideotype of root traits to optimize water acquisition, “Steep, Cheap and Deep,” in which brace roots with high occupancy and reduced lateral formation could contribute to rooting depth, thus enhancing water uptake under drought in maize.

33. Laura Satkowski, University of Missouri, Columbia, MO, USA

Sorption and transport of imidacloprid in agroforestry buffer, grass buffer and cropland soils

The objectives of this study are to: (1) determine the sorption of the neonicotinoid imidacloprid (ICD) by measuring the partition coefficient, K_D, values of soil collected from three different vegetative managements; (2) study differences of potential leaching of ICD by constructing breakthrough curves through soil columns; (3) determine transport and reaction parameters of ICD in soil from the three different vegetative managements using an inverse modeling technique with the computer program HYDRUS-1D. Soil collected from six locations in northern Missouri with adjacent crop, grass and agroforestry land uses were tested for ICD sorption values using end-over-end shakers. Soil from the location with the greatest difference in crop, grassland and agroforestry K_D values was used for soil column experiments. Leachate was collected for 600 h from columns uniformly packed with soils from each land use and analyzed using high pressure liquid chromatography.

For all locations, the agroforestry K_D values were higher than the cropland K_D values to the 0.05 significance level, indicating that ICD has a greater affinity to sorb to agroforestry than cropland soil. After 600 h, 92% of the ICD had leached from the cropland soil columns. The grassland and agroforestry columns are currently running. Due to higher K_D values in grassland and agroforestry soil, it is predicted that after 600 h, less ICD will have leached out of the soil columns, indicating grassland and agroforestry buffer strips have the potential to retain ICD, preventing it from entering aquatic systems. The HYDRUS 1D analysis has not been completed, but it is predicted the soil planted to grass and agroforestry buffer strips will have a higher percentage of instantaneous and irreversible sites than the soil planted to row crops due to higher specific surface area and chemical reactivity in the grass and agroforestry soil.

34. S. Assouline (ARO, Volcani Center, Israel), M. Möller, A. Furman, K. Narkis, A. Silber

Impact of water regime and growing conditions on soil–plant interactions: from single plant to field scale

Global water resource quantities and qualities are declining, but at the same time, a strong demand for higher agricultural productivity continues to emerge due to population growth. This calls for a significant increase in irrigation and fertilization efficiencies and requires improving our understanding of the interactions between plants and their physical environment.

The main objective of this study is to analyze the combined effect of varying drip irrigation management techniques and growing conditions (media properties and container volumes) on soil–plant interactions. In a series of experiments, irrigation flow rates and intervals ranging from 2 d to 10 min were applied to the vegetative stage of a test crop (bell pepper [*Capsicum annuum* L. 'Selika']) cultivated under different growing conditions: sand and perlite in buckets, perlite in containers, and loamy sand under field conditions.

Data on soil water regime, plant water uptake, and plant development were monitored in each setup. Large differences were observed in terms of both root and canopy development in response to the different application rates and frequencies. The prevailing irrigation management reflects on the soil water content dynamics, and consequently, on the plant water uptake and growth. Sap flow rate measurements indicated that higher irrigation frequency or lower water application rates increased plant water uptake rates. However, in most cases (except for the sand), it also led to a lower root mass and a smaller root mass/leaf area ratio. Interestingly, in the single

plant per bucket experiments, a larger leaf area seemed conditioned on a larger root mass, while the opposite was the case in the two experiments in which plants were grown in rows (perlite in containers and loamy sand field), where the most prolific canopy development was supported by the smallest root mass. Integrating the findings across the different experiments, we introduce the concept of mean daily available water volume per plant as the product of container/bucket volume and mean daily water content in the medium to express the joint effect of constraints imposed by the physical volume of the growing medium and its specific hydraulic properties.
The mean daily available water volume per plant was found to be positively correlated with the dry root mass to leaf area ratio.