Core Ideas

- This special section has 15 contributions focused on physical and biochemical processes in the root zone.
- Contributions stem from presentations at the 2016 Kirkham conference in Sede Boqer Campus, Israel.
- The root system plays a key role in water, nutrient, and gas transport processes in the vadose zone.
- Novel measurement and modeling tools are still needed to understand and manage root zone processes.

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The Root Zone: Soil Physics and Beyond

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This special section of *Vadose Zone Journal* (VZJ) contains 15 contributions focusing on the physical, biological, and chemical aspects of water and solute transport into and through the soil root zone, including root water and solute uptake. The papers stem from presentations at the 2016 Kirkham Conference, "The Root Zone: Soil Physics and Beyond," which took place at the Sede Boqer campus of Ben-Gurion University of the Negev, Israel, during 10 to 14 April (https://www.soils.org/membership/divisions/soil-physics-and-hydrology/kirkham-conferences). Much consensus existed at the conference for a special VZJ section to reflect the importance of the soil root zone from many disciplinary perspectives (soil, environmental, agricultural, hydrologic, and atmospheric) and the complexity of the basic processes involved. The contributions deal with root zone processes at different scales and from different disciplinary viewpoints, while covering a broad range of topics from the very theoretical to important practical applications. Special emphasis is on novel measurement and modeling tools at various scales and the need for interdisciplinary research.

Abbreviations: ERT, electrical resistivity tomography; SPAC, soil–plant–atmosphere continuum; VZJ, *Vadose Zone Journal*.

Available fresh water resources have been decreasing considerably during the past several decades due to less overall availability, contamination, and increasing competition between agricultural and many other users. At the same time, the need for food production has been increasing constantly (Foley et al., 2011). Increasing resource use efficiency is hence of great importance. Clearly, the root system and its interactions with the soil as such and the larger scale hydrologic environment plays a key role in determining overall water, nutrient, and gas transport processes. Understanding and quantifying these processes will facilitate increased resource-use efficiency that will ultimately lead to sustainable agricultural and environmental management, ensure food security, and reduce the waste of limited resources.

The root zone is the main terminal through which vegetation obtains its resources as well as a critical part of the upper vadose zone in terms of partitioning rain and irrigation water into evaporation, transpiration, runoff, and deep drainage. While being one of the most important components of the soil–plant–atmosphere continuum (SPAC), the root zone is also one of the least understood parts. The rhizosphere, as first termed in 1904 by Lorenz Hiltner, is the interfacial region between soil and vegetation, controlling the movement of water, nutrients, and other commodities into plants (McNear, 2013).

This special section of *Vadose Zone Journal* (VZJ) contains 15 contributions resulting from presentations at the 2016 Kirkham conference, which took place at the Sede Boqer campus of Ben-Gurion University of the Negev in Israel in April 2016. Participants at the conference identified several key processes and data requirements that must be addressed to more fully understand and manage soil root zone processes. These include: (i) water flow and uptake; (ii) solute transport and uptake; (iii) root respiration and soil aeration; (iv) root morphology and its dynamics in time; and (v) properties of the interface between roots and soil (i.e., the rhizosphere). In the following, we elaborate on each of these specific areas relative to the research described in the 15 contributions of this special section.

Water Flow and Uptake

Water potential gradients provide the driving force inducing flow within and between adjacent compartments in the SPAC (Kirkham and Powers, 1964; van der Ploeg et al., 2008). This concept was first formulated by using the similitude of Ohm's law for steady electric current flow in a resistance network (Gradman, 1928; van den Honert, 1948; Molz, 1981; Feddes and Raats, 2004). Accordingly, the steady water flux through roots, stem, and leaves within the SPAC can be expressed as the product of the difference in the water potential between any two compartments and a proportionality factor, either the conductance or resistance of the transmitting medium. The definition of the proportionality factor is context dependent, whether soil or plant, according to the spatial scale of the water-transporting medium (Hopmans and Bristow, 2002). The overall resistance is defined as a series combination of all resistances in the SPAC (Campbell, 1985). Potential differences between soil water and atmospheric water vapor typically amount to tens of megapascals. As the soil dries, the soil water potential decreases, leading to a subsequent reduction in the hydraulic conductivity. To maintain the water potential gradient in terms of driving the transpiration stream, the root-water potential must decrease below that of the soil. But while the soil-water potential can decrease to very low values, the root-water potential is limited by a critical value, around -1.6 MPa for most agricultural crops (Koorevaar et al., 1983), below which plants wilt and die.

Several papers in this special section addressed the problems of water uptake by plants and how to improve models describing root water uptake. A first set of contributions built on the single-root radial flow concept of Gardner (1960). This approach assumes that the root is fully surrounded by soil and that complete contact exists between the root surface and the surrounding soil. However, the contact area between roots and the soil matrix can be reduced for roots growing in large (bio)pores, especially when roots and soil shrink during drying or when roots grow into or across large pores between soil aggregates. De Willigen et al. (2018) presented analytical solutions for the case of partial root–soil contact and investigated to what extent partial root contact influences the time period during which water and nutrients can be taken up at their potential rate. Pinheiro et al. (2018) also used an analytical solution for radial flow to explore various ecological zones in Brazil. They developed a multilayer root water uptake model based on the matric flux potential. Soil hydraulic properties from two different ecological zones were assessed. They concluded that the water supply capacity of semiarid soils may be higher than those of humid regions and that a decrease in the critical root pressure head below -150 m will not significantly affect water availability to vegetation. Their results indicate that increasing the root density in upper soil layers may well be a more efficient strategy for ecosystems to acquire water in semiarid regions.

Another modeling approach couples water flow in the soil to flow within the root system. Models of this type are able to describe water redistribution processes in the root zone in conjunction with flow in the root system, including hydraulic lift. Meunier et al. (2018) used such a model, along with experimental data and stable isotopes, to evaluate the magnitude of hydraulic lift in a rhizobox planted with Italian ryegrass (*Lolium multiflorum* Lam.). They estimated that the amount of water that moved at night from relatively wet deeper soil layers via the root system to drier upper soil layers was about 20% of the next day's transpiration. As for water uptake, water release was found to depend also strongly on the soil resistance to flow in dry soils. Ignoring small-scale flow processes in soil around the roots would lead to considerable overestimation of the water release rate. Measurements of stable water isotopes could be used to estimate soil and root system hydraulic properties by inverse modeling. Replacing traditional techniques using water extracts from destructively obtained soil samples by newly developed nondestructive sampling techniques could therefore open new avenues for process-based root zone research.

Considering water fluxes and resistances to flow within the root system is also important for relating water potentials in the root zone to plant water potentials and plant water stress and describing the redistribution of root water uptake when water potentials are not uniform in the root zone. Cai et al. (2018) used an upscaled soil–root water flow model that considers the plant water potential and an effective root system conductance to describe water transfer from the soil to the plant. Their model was implemented in HYDRUS-1D and compared with other root water uptake functions. Soil and root parameters of winter wheat (*Triticum aestivum* L.) were derived from observations of root density, soil water content, and water potential using inverse modeling. The various models simulated similar water contents, water potentials, and transpiration rates, but different profiles and dynamics of root water uptake resulted when only the soil–root model was used to simulate water release at night in dried-out soil layers. Still, the impact of these differences on soil water contents and water potentials were too subtle to be detected by the adopted sensors. The use of other data types, such as stable water isotopes (see Meunier et al., 2018) for estimating water uptake and release profiles, are therefore promising to discriminate between different water uptake models. Inversely estimated root system conductances could be compared with direct estimates calculated from literature data about axial and radial conductances of root segments. This demonstrates that the root water uptake parameters of macroscopic models can be derived from directly measurable plant and crop properties.

Root density profiles provide other important input information for root zone process models. Zhu et al. (2018) found that using dynamic root density profiles of a winter wheat crop, instead of assuming a fixed root density distribution, improved the accuracy of soil moisture and soil water potential simulations and crop transpiration. Their model was used to evaluate the contribution of capillary rise from the groundwater to transpiration of winter wheat in the Huaihe River basin (China) for different water table depths and for wet, normal, and dry growing seasons. Accurate estimates of the

groundwater contribution to transpiration were important to estimate irrigation water requirements and avoid excessive irrigation and leaching of agrochemicals to the groundwater.

Solute Transport and Uptake

Nutrients are transported toward plant roots by advection and diffusion in the soil solution; this solution flows along a pressure gradient created by root water uptake, which dries the area in direct proximity to the roots (Kirkham and Bartholomew, 1955). The soil solution of water and nutrients may enter the root by apoplastic flow and, from intercellular spaces, may be taken up actively or passively into cells. The passage of ions across plant cell membranes is called *active* if it is contrary to the gradient of the electrochemical potential energy and *passive* if it crosses with a downward energy gradient into the cell (Šimůnek and Hopmans, 2009). In process models that simulate solute transport in the root zone, the notions of active and passive uptake are linked to the overall uptake process. If the nutrient uptake rate is equal to the water uptake rate multiplied by the bulk pore water concentration, then transport is often considered to be passive. However, this concept may be too simplistic to describe interactions between actual uptake and solute concentrations at the soil–root interface. De Willigen et al. (2018) assumed that the uptake rate is determined by the demand of plants and can be maintained as long as the concentration at the soil–root interface is above a certain critical value. They showed how the time period for which the uptake rate can be sustained by the supply rate depends on the contact of the roots with the soil. They found that radial partial contact had less impact than axial partial contact and that correction of the effective root density by a factor equal to the partial contact fraction led to underestimation of the potential uptake time for partial radial contact and overestimation for axial partial contact. Besides nutrient uptake, water uptake also can be influenced by solute concentrations at the soil–root interface when osmotic potentials in the pore water become an important component of the total water potential. Using simulations, Jorda et al. (2018) evaluated the impact of convergent flow and transport of salts toward the root surface on solute accumulation and osmotic potentials. Differences in concentration and the osmotic potential between the root surface and the bulk soil solution increased with increasing transpiration and decreasing root density. This implies that parameters of stress functions that are used in macroscopic root zone models to describe reductions in water uptake as a function of the bulk soil osmotic potential should be a function of the plant transpiration rate and the root density.

Spatial variations in the solute concentration and osmotic potential of the root zone can also have an effect on root water uptake at the macroscale. Berezniak et al. (2018) demonstrated how solute distributions in the root zone of row crops can be manipulated by generating variations in texture between the root zone and the interrow. Using a soil with coarser texture in the root zone and finer texture in the interrow leads to flow of water and salts out of the root zone toward the surface in the interrow

material. The resulting capillary barrier effect avoids backflow and transport of salts into the coarser soil material of the root zone. Hence, generating a spatial variation in soil texture may well be a possible management practice for controlling water and salinity in irrigated fields.

Root Respiration and Soil Aeration

Rates of respiration by plant roots and soil microorganisms depend on the levels of soil O_2. Movement of O_2 from the atmosphere into the rhizosphere occurs mainly through diffusion via the gas phase (Jensen and Kirkham, 1963). The diffusion coefficient of O_2 in air (about 1.8×10^{-1} cm^2/s) is some four orders of magnitude greater than the diffusion coefficient in water (about 2.4×10^{-5} cm^2/s). Therefore, diffusion of O_2 is practically absent in soils when the fraction of air-filled pores becomes <10% (Wesseling and van Wijk, 1957). Jayawardane and Meyer (1985) similarly suggested that the air-filled porosity needs to be >8% at all times to supply sufficient O_2 to wheat roots. Before entering respiring roots, O_2 further needs to diffuse through water and/or biofilms or a layer of mucilage surrounding the roots (van Noordwijk and de Willigen, 1983), which is another limiting factor. Maintaining a balance between water and O_2 contents that are favorable for optimal plant growth requires management strategies that are based on a sound understanding of soil aeration and plant respiration processes. For example, fine-textured soils are more prone to O_2 deficiency after irrigation than are coarse-textured soils; O_2 diffusion rates in fine-textured soils can be up to 30 times smaller than those in coarse-textured media (Drew, 1990).

Ben-Noah and Friedman (2018) presented a comprehensive review and evaluation of respiration (including both plant and soil microorganisms) and aeration processes. They compiled a large number of references, from which they concluded that: (i) movement of O_2 from the atmosphere into the soil profile and the rhizosphere is dominated by diffusion; (ii) respiration in the soil is comprised of plant roots and microbial O_2 uptake (roughly equivalent to several grams of O_2 per square meter per day); (iii) the O_2 diffusion rate (ODR), the soil-air O_2 concentration, and the soil air (or water) content are better indicators of O_2 availability to plants than indirect indicators such as redox potential or soil characteristics; and (iv) forced soil aeration methods (e.g., adding air, O_2, or H_2O_2 to irrigation water, injecting air more directly into the soil, or applying slow-release peroxide to the soil) showed mostly favorable results.

Root Morphology and Its Dynamics

When soil moisture conditions are optimal, plants' ability to utilize available water and nutrients from a soil layer is primarily determined by the root density of that layer (Phillips and Kirkham, 1962). While the bulk of plant roots center around the root crown near the soil surface, plants allocate carbon pools to increase the excavating capacity of roots for untapped soil water and nutrients.

By widening and deepening the root zone, plants hence are able to meet their ever-increasing "thirst" throughout the growing season. While the relation between root density and root water uptake is positive, however, arriving at an accurate representation of the root morphology necessary for uptake modeling is not simple (Raats, 2007), nor is there an established protocol by which a root distribution should be quantified. The root density generally decreases with depth, but the manner by which the roots thin out along the soil profile remains a topic of discussion. Not only is root development unique for each plant type, its features are also influenced by soil texture, soil water status, nutrients (e.g., P), and O_2 availability. Prasad (1988) assumed a linear root distribution with depth, resulting in linearly decreasing extraction rates along the soil profile for optimal moisture conditions. Feddes et al. (1974) and Gerwitz and Page (1974) reported that in most instances an exponential function is sufficient for characterizing crop root distributions. Parameterizations of the root density with depth often require geometric information about the roots, which is not easily obtained (Raats, 2007). Such metrics as root length per unit root volume, root surface area per unit root volume, and root and soil volume fractions remain difficult to obtain.

The importance of having an accurate representation of root system properties, such as the root density distribution and how it changes with depth during the growing season in root zone process models, was also highlighted in several contributions to this special issue (Zhu et al., 2018). While normalized root density distributions are generally used in macroscopic models, other properties of the root system such as the absolute root density (de Willigen et al., 2018; Jorda et al., 2018; Pinheiro et al., 2018) and root segment and root system conductances (Meunier et al., 2018), which can be related to the total root length (Cai et al., 2018), can be used also to link plant stress functions to root system properties.

Aidoo et al. (2018) investigated the interaction between shoot and root development of a commercial pepper (*Capsicum annuum* L.) hybrid, which was either grafted to a new rootstock hybrid (S101, Syngenta), self-grafted, or ungrafted and which experienced low temperatures at the start and high temperatures at the end of the growing season. They evaluated whether grafting is a potential adaptation strategy as an alternative to breeding new cultivars that are better adapted to high and low temperatures. The stronger root development of the grafted cultivar had an impact on soil electrical conductivities and chloride contents, which suggested that water uptake and root activity of the rootstock was less sensitive to the low soil temperatures at the beginning of the growing season. This increased activity was accompanied by more transfer of C and N between the shoot and root. In a related study, Hartmann et al. (2018) developed a root growth module that was adapted and implemented into the HYDRUS software packages to simulate root growth as a function of various environmental stresses such as temperature, aeration, and soil chemical properties. In particular, the newly developed add-on module was used

to evaluate the effects of temperature on root growth using experimental data. Sensitivity analysis revealed that parameters defining the growth rate or the shape of the temperature stress function had greater influence on the modeling results than the maximum rooting depth and cardinal temperatures. The small number of additional calibration parameters makes the modeling approach of environmental-stress-dependent root growth a convenient add-on to the HYDRUS models.

Root growth may also be affected by the presence of pathogens. Peddinti et al. (2018) used electrical resistivity tomography (ERT) to image water distributions in the root zone of irrigated healthy and *Phytophthora*-infected mandarin orange trees. From the ERT images, they derived parameters of the root density distribution using inverse modeling. They found that the extent of the root zone of the infected tree was smaller and had lower water uptake and transpiration rates than the healthy tree. The reduced root water uptake by the infected tree should be accounted for in irrigation scheduling because overirrigation can lead to wet soil conditions that are more suitable for the proliferation of pathogenic fungi.

◊ Properties of the Interface between Roots and Soil: The Rhizosphere

The interface between the root surface and the soil, i.e., the rhizosphere, plays a critical role in root–soil processes. Proper characterization of the rhizosphere, which differs in biological, chemical, and physical properties from the bulk soil (Hinsinger et al., 2009), and its implementation in root-zone process models is therefore of great importance.

Several papers in this special issue addressed properties of the rhizosphere. Naveed et al. (2018) investigated the effect of barley (*Hordeum vulgare* L.) and maize (*Zea mays* L.) root exudates or mucilage and chia (*Salvia hispanica* L.) seed mucilage, which is often used as a model mucilage, on the mechanical and hydraulic properties of soils with different texture using rhizosphere-scale mechanical and hydraulic tests. Mucilage increased the mechanical stability and reduced the wetting rate of the rhizosphere, but the effects depended on the type of exudates and the soil texture involved, with a greater effect for chia seed exudates and coarse-textured soils.

Benard et al. (2018) used light microscopy to investigate how the distribution of mucilage within pores affects the wettability of the rhizosphere. Upon drying, mucilage receded into smaller pores where, at low mucilage concentrations, thin filaments were created to connect grains. By contrast, hollow tube-like structures formed at higher mucilage concentrations, which then filled a large fraction of the pore space. The thin filaments did not have an effect on fluid flow properties and water repellency of the porous medium, whereas the tube-like structures could block flow processes. This

explains the threshold-like behavior of water repellency as a function of mucilage concentration in treated and undisturbed soil–mucilage mixtures. The properties of the mucilage in the rhizosphere could be manipulated by adding surfactants or rhizoligands, as was shown by Ahmed et al. (2018). Rhizoligands can rewet the rhizosphere faster and reduce swelling of the mucilage, thereby reducing the hydraulic conductivity of the rhizosphere. Using neutron tomography, Ahmed et al. (2018) observed that adding rhizoligands caused relatively fast rewetting of the rhizosphere. While the transpiration rate was initially reduced due to the lower conductivity of the rhizosphere, the rate could be sustained for a longer time period. Application of rhizoligands to the root zone hence is a possible management strategy for reducing the severity of water stress while maintaining moderate stress levels. Kroener et al. (2018) proposed a conceptual model of how mechanistic pore-scale interactions of mucilage, water, and soil depend on pore size and mucilage concentration and how these pore-scale characteristics result in changes in the macroscopic soil hydraulic properties. They also examined the water retention and saturated hydraulic conductivity of soils with different ranges of particle sizes, mixed with various mucilage concentrations, to validate the conceptual model. They found that: (i) at low mucilage concentrations, the saturated conductivity of a coarse sand was a few orders of magnitude higher than that of a silt; (ii) at intermediate concentrations, the hydraulic conductivity of a fine sand was lower than that of a coarse sand and a silt; and (iii) at high concentrations, all soils had hydraulic conductivities of the same magnitude. Ben-Noah and Friedman (2018), in their review, further discussed the effect of a mucilage layer around roots on reducing the aeration of roots. This implies that rhizosphere management should also consider root aeration.

⬥ Concluding Remarks

Held once every 4 yr, the Kirkham Conferences are topical meetings designed to encourage participants to make organized in-depth explorations of disciplinary and interdisciplinary topics relevant to soil physics and related sciences in ways seldom possible at national or international meetings. The main message from the 2016 conference was that more experimental and modeling efforts are needed to better understand and quantify the complex interactions operative at multiple scales within the soil root zone and to do so while building bridges to other research communities and disciplines. We hope that the manuscripts in this special section help to reduce some of the scientific gaps in our knowledge of the root zone and inspire future research. Not all topics relevant to the root zone were included in this special section. For example, there were no contributions on the topic of the rhizosphere microbiome and its role in soil–root processes, which indicates the need for future research. We believe that the rhizosphere microbiome is an emerging topic that can be a platform for innovative studies combing biology and soil physics in more intricate ways. Studies that include soil, plant roots, and rhizobacteria will lead to a more complete understanding of root zone processes and, ultimately, effective strategies to meet the challenges of water and nutrient shortage and to ensure food security for a growing population and under a changing climate.

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