Special Section: Soil–Plant–Atmosphere Continuum

# Interweaving Monitoring Activities and Model Development towards Enhancing Knowledge of the Soil–Plant–Atmosphere Continuum

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The study of water pathways from the soil to the atmosphere through plants—the so-called soil–plant–atmosphere continuum (SPAC)—has always been central to agronomy, hydrology, plant physiology, and other disciplines, using a wide range of approaches and tools. In recent years, we have been witnessing a rapid expansion of interweaving monitoring activities and model development related to SPAC in climatic, ecological, and applications other than the traditional agrohydrological, and it is therefore timely to review the current status of this topic and outline future directions of research. The initiative for the special section of *Vadose Zone Journal* on SPAC emanated from several sessions we recently organized in international conferences and meetings. With a view to the specific research questions covered in this special section, this article introduces and reviews SPAC underlying issues and then provides a brief overview of the invited contributions. We have grouped together the 15 contributions under three main sections related to the local, field, and landscape spatial scales of interests. Within these sections, the papers present their innovative results using different measuring techniques (from classic tensiometers and TDR sensors to more advanced and sophisticated equipment based on tomography and geophysics) and different modeling tools (from mechanistic models based on the Richards equation to more parametrically parsimonious hydrologic balance models). They provide a snapshot of the current state of the art while emphasizing the significant progress attained in this field of research. New technological developments and applications are also highlighted.

Abbreviations: SPAC, soil–plant–atmosphere continuum

**Soil is a key component** of the earth's biosphere linking surface water and groundwater and the atmosphere. Most soil hydrological processes take place over vegetated land areas, and therefore the plant rooting system becomes the most active zone for transfer of water (and dissolved nutrients) between soil and atmosphere through the plants.

Parallel to early attempts at quantitative and mechanistic description of water flow in soil (Buckingham, 1907; Gardner et al., 1922; Richards, 1931) and in the absence of methods for measurement of energy state of water in the soil–plant system, Veihmeyer and Hendrickson (1927) proposed a simple concept for estimating available water for plant growth based on soil water content values at field capacity and permanent wilting (Romano and Santini, 2002). This simple conceptual model was originally developed for irrigation scheduling and water management, but soon was adopted by hydrologists for modeling of rainfall–runoff processes and other soil hydrological processes (Horton, 1933).

Realistic flows of water in the soil and concurrent plant root water uptake are highly dynamic phenomena that are far more complex than simplified by the field capacity concept, involving cycles of soil wetting and drying. These cycles are essentially driven by infiltration and redistribution processes, and reflect stomatal control of transpiration, aimed at regulating plant water use during periods of water shortage. Through advances in (i) accurate measurements of water status across the SPAC and (ii) the establishment of the water potential concept, it became evident that the soil–plant–atmosphere system required a more comprehensive treatment. Plant available water is not an intrinsic soil characteristic, but it is affected by plant types and weather conditions. The latter imposes the time-varying transpiration demand, whereas the former regulates the amount of water being extracted from the soil's rooting zone and is dominated by stomatal control. A better understanding of these complex processes, along with those concerning plant water homeostatis and differentiation of flow resistances across SPAC, has definitely led to more accurate

The guest editors summarize the advances and challenges associated with monitoring and modeling of the soil–plant–atmosphere continuum. They introduce the contributions in the special section, with an emphasis on the scale addressed in each study.

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descriptions of plant water stress conditions. In short, it was the consolidation of the soil–plant–atmosphere unifying concept that has enabled the advancement of our understanding of the processes taking place in the system (Cowan, 1965).

Advances in the determination of soil hydraulic properties, basically the soil water retention and hydraulic conductivity functions, as well as the introduction of macroscopic approaches to describing root water uptake, have promoted the use of mathematical models based on the one-dimensional Richards equation:

$$C(h)\frac{\partial h(z,t)}{\partial t}=\frac{\partial}{\partial z}\left\{K(h)\left[\frac{\partial h(z,t)}{\partial z}-1\right]\right\}-S\left[h(z,t)\right] \quad [1]$$

In Eq. [1], $t$ is time, $z$ is vertical coordinate (taken positive downward), $h$ is matric pressure head, $C(h) = \mathrm{d}\theta/\mathrm{d}h$ is the water capacity function, which can be readily obtained from knowledge of the soil water retention function, $\theta(h)$, and the hydraulic conductivity function, $K(h)$, with $\theta$ being the soil volumetric water content. The so-called sink term, $S[h(z,t)]$, accounts for the extraction of water by spatially distributed roots with different expressions developed by various authors (e.g., Nimah and Hanks, 1973; Feddes et al., 1974; Raats, 1976; Molz, 1981; Molz and Remson, 1970; Santini, 1980, and others). The transfer of water from the plant to the atmosphere is modeled by different relationships, commonly obtained through an energy balance method (Monteith and Unsworth, 1990).

Coupling of monitoring and modeling activities, either within or between different research groups and even performed with different purposes, has contributed to significant progress. The determination of soil hydraulic properties using various direct, inverse, or indirect methods, with their estimation of spatial variations with geostatistical or stochastic tools, has opened new horizons in describing the evolution of soil–plant–atmosphere processes over different spatial scales of interests—from the single plant to plot, hillslope, or the catchment. It is interesting to note that in a way similar to the synergism between monitoring and modeling issues, the characterization of soil hydraulic behavior has evolved by increasingly focusing on the development of methods not disjoined from the identification of relevant spatial patterns (Romano, 2004). The variability is significant at all scales of interest, and solving the scaling problem is still a challenging issue (Hopmans et al., 2002). In this respect, GIS and remote sensing techniques are also great help in providing the hydrologic balance models with crucial information on vegetation status and upper boundary conditions.

The need to verify the validity of the Buckingam–Richards theory has led to a continuous refinement of experimental methods and sensors. While the tensiometer has been used in the field and under laboratory conditions for the measurement of soil water matric potential, indirect measurement of soil water content has evolved significantly during the last 20 yr (Robinson et al., 2008; Vereecken et al., 2008). This includes soil moisture sensors that are nuclear-based (gamma-ray and neutron sensors) and those that are permittivity-based (TDR and capacitance sensors). Their use spreads from examining patterns of soil water extraction by plant roots at local scales to the description of soil moisture dynamics at catchment scales or larger. The ability to measure soil water retention in situ can be used to improve the accuracy of numerical models (van der Ploeg et al., 2010). In the pursuit of reconciling data and models, the creation of long-term environmental observatories (Lin et al., 2011) is gaining considerable attention, especially toward addressing some important questions regarding climate change, the increased competition for natural resources (soil, water, and vegetation), and toward harmonizing technological progress, environmental quality, sustained equity, and quality of life.

The temptation to model every detail of SPAC often clashes with the lack of required information on model parameters and boundary conditions, especially when one has to solve relevant problems at larger scales. As an example, variables are often monitored to provide the model with accurate evapotranspiration fluxes, but fail to provide a closer examination of the lower boundary condition at the bottom of the soil profile. A unit total head gradient is commonly assumed for the lower boundary of the computational flow domain, thus setting the bottom water flux density equal to the unsaturated soil hydraulic conductivity. We note that this soil parameter is typically unknown and is highly variable and uncertain.

Alternatively, the concept of modeling dominant hydrologic processes using zero-dimensional models is proposed to overcome some of the above-mentioned difficulties (Grayson and Blöschl, 2000; Milly, 2001; Rodriguez-Iturbe and Porporato, 2004). One example of such development philosophy is the single-layer bucket model describing soil moisture dynamics at the daily time-scale in a probabilistic fashion (Guswa et al., 2002). The governing stochastic linear ordinary differential equation for the soil layer of depth $Z_\mathrm{r}$ is defined as follows:

$$nZ_\mathrm{r}\frac{\mathrm{d}s(t)}{\mathrm{d}t}=I\left[s(t),t\right]-E\left[s(t)\right]-T\left[s(t)\right]-L\left[s(t)\right] \quad [2]$$

where $n$ is soil porosity, and $s$ $(0 \leq s \leq 1)$ is the average degree of soil saturation over the entire rooting zone, $I$ is the rate of rainfall infiltrating into the soil, $E$ is the actual evaporation rate, $T$ is the actual transpiration rate, and $L$ is the leakage rate.

Equation [2] is a commonly used model for ecohydrological studies, which have gained acceptance as evidenced by seminal studies such as Porporato and Rodriguez-Iturbe (2002) and others. Conceptually, these studies conduct both numerical and observational experiments aimed at retrieving plant responses to various environmental drivers by linking water availability with ecosystem vitality (D'Odorico et al., 2010). A major issue in the ecohydrological discipline is the interpolation and extrapolation of transport processes across spatial or temporal scale ranges. This "scale-transfer problem" is tackled with both advanced modeling tools and new data sets to describe the soil–plant–atmosphere system behavior across scales. In many cases, soil moisture dynamics and climate seasonality now seem to play a crucial role for a reliable description of ecohydrologic processes, which should not be assumed as simply stationary all the time.

More recently, particular attention is paid to "ecosystem services" (Costanza, 2008). Goods and services of a natural environment are precious resources for humankind and help to support our society, but they are also vulnerable and have to be exploited with great care. The resulting benefit analyses of ecosystems have proven to be very difficult, partly because of the interconnections and feedbacks among processes and the strong link to social and economic aspects. Again, allowing also for questions of climate variability and land-use changes, current research on soil–plant–atmosphere systems is generating valuable results on identifying suitable ecosystems securing the provision of hydrologic services. Such analyses also represent an effective way to find operational and harmonized tools to interpret measurements and processes so that their information content can be transferred to the larger domain of practical application.

The above-mentioned questions have been discussed in several conferences and workshops. Specifically, they have long been the key topics of the following sessions at the General Assembly of European Geosciences Union: "Monitoring and Modeling for Transfer Processes in the Soil–Plant–Atmosphere Continuum," organized mainly by N. Romano and R. Angulo-Jaramillo, and "Soil–Plant Interactions from the Rhizosphere to Field Scale," organized mainly by M. Javaux and M. van der Ploeg. This special section is a companion and a natural extension of the special section on "Roots and Root Functioning" published in 2008 in *Vadose Zone Journal* (Skaggs and Shouse, 2008). We wish to close this introductory note with the hope that the papers collated in this special section of *Vadose Zone Journal* give rise to some reflections on our current knowledge on that topic and contribute in sketching out future directions of research.

## Brief Overview of Soil–Plant–Atmosphere Continuum Section Papers

In the following we group the papers presented in this special section based on relevant spatial scales and analysis techniques.

### Local Scale

At the local spatial scale, understanding water and nutrient uptake by plant roots still represents a major challenge in biology, but also in soil science. New methods such as magnetic resonance imaging (MRI) and tomography are applied to study subterranean parts of plants (see also Skaggs and Shouse, 2008). In their contribution, Moradi et al. (2012) explained the unexpected behavior of the rhizosphere observed by using neutron tomography, that is, lower soil water content in the rhizosphere compared to the bulk soil after rewetting. Measuring rhizosphere and soil wettability properties, they found significantly higher contact angles for rhizosphere soil compared to the bulk soil after drying, which indicates slight water repellency in the rooting zone.

Alternatively, a main difficulty in the investigation of root uptake is to quantify local mass fluxes in different parts of the root system. Zarebanadkouki et al. (2012) proposed the use of neutron tomography in combination with a deuterated water $D_2O$ injection to quantify water uptake along root segments of a lupin plant. They observed a day–night variation in transport within and along the root segments. A simple convection–diffusion model that assumed the endodermis as the main resistance to water transport enabled them to quantify the root axial flux.

### Plant Scale

How local plant root specific properties and soil property spatial variation at the plant scale combine for resulting into a unique integrated plant response like the transpiration flux or a mass uptake is also an important issue. Bridging this scale gap between root processes and plant behavior is a key step for strengthening the foundations of plant scale models and improving their prediction capabilities.

Schnepf et al. (2012) addressed this issue for phosphorous uptake. They combined a local P uptake model, which describes the transport and competitive sorption of P and citrate in soil with three-dimensional plant growth model to assess how plant properties and rhizosphere impact P uptake. Applying it for a young oilseed rape root system growing in a rhizotron, they showed that young parts of the root system are responsible for most of the P uptake after 16 d.

A similar approach was used by Schröder et al. (2012) for studying the impact of plant on solute spreading in soil. By using a three-dimensional mechanistic model of water flow in the soil and in the root coupled with a particle tracking code, they investigated in silico how root architecture, plant solute uptake mechanisms (passive, active, and solute exclusion), and plant transpiration rate affected the three-dimensional water velocity field and, thus, the effective dispersivity length. They observed a change of dispersivity in a range of 50%, depending on solute redistribution in the root zone, which questions the use of bare soil-derived dispersivity values to predict one-dimensional solute spreading in cropped field.

These two studies illustrate how mathematical modeling may increase insight into underlying root–soil processes and upscaling of low-scale processes at the plant scale. Another use of modeling is for predicting plant water uptake and stress onset, as well as, for example, refining irrigation recommendations. In such a case, simple models are often used today. Although one may wonder to what extent more complex, mechanistic models may simulate different behavior. De Willigen et al. (2012) investigated this question by comparing predictions of four root water uptake models with increasing levels of complexity and dimensions under extreme conditions: low root length density, high transpiration rate, and low water content. They observed that differences between the models were a function of the soil texture, the boundary conditions, and the studied variable. In general, model results were more similar under high conductive soils.

In addition to modeling, experimental studies are crucial for improving our understanding of root water uptake. Vandoorne et al. (2012) performed an experimental study on chicory roots to assess how water stress affected root water uptake and growth. Using a one-dimensional Richards-based model with a stress function and a compensation mechanism, they successfully retrieved the evolution of the actual sink-term profiles. They showed that under water-limited conditions, passive compensation mechanism allowed chicory roots to take water deeper in the soil in a first stage. Later, plants adapted by generating new lateral roots in wetter horizons.

## Field Scale

When moving from the local root zone scale toward the plot and field scales, different modeling tools and monitoring protocols must be applied to better detect changes in ecosystem functions and processes under specific situations.

To capture the relevant interrelations between soil structure (as it can be imaged via noninvasive geophysical methods), ground cover, and soil moisture dynamics, Cassiani et al. (2012) presented the results of long-term monitoring and irrigation tests performed on an experimental farm in Southern Sardinia, where the main goal of the experimental activities has been to collect information about the hydrologic behavior of a Mediterranean catchment, ranging from the small scale of the soil profile to the larger catchment scale. A 3-d infiltration and redistribution experiment was conducted to understand the soil–vegetation interactions at the plot scale and how they can affect the soil water balance, particularly in view of possible climatic changes. Relevant feedback between infiltration and vegetation growth has been demonstrated to be ground-cover specific. An aspect of this contribution that deserves attention is the attempt to interpret the biomass and water dynamics in the light of a parsimonious conceptual modeling framework. This modeling exercise, albeit preliminary, shows what can be obtained with a limited amount of input data and, more importantly, can be viewed as an approach to ascertain what kind of dataset should be collected during subsequent field campaigns to better parameterize and validate ecohydrological models.

Basso and Ritchie (2012), using literature data and newly validated simulation results with the SALUS model, demonstrated that surficial soil moisture conditions and the highly variable sensible heat transfer in crops with sparse canopy significantly affect the amount of transpiration and soil evaporation. The authors clearly pointed out that simulated transpiration to estimate plant growth or plant growth simulations to estimate transpiration provide unrealistic results when management influences yield and/or water supply is fixed or not limiting. Furthermore, they showed that when yield is increased by better crop management and improved cultivars, water use efficiency is also increased, but evapotranspiration remains unchanged.

To save water, drip irrigation is commonly used, making point source models of interest for management of irrigation. Communar and Friedman (2012) presented a solution to the steady infiltration from surface point sources into a two-layered, cylindrically (un)confined soil domain, with root water extraction from the upper layer and evaporation from the soil surface. They used a linearized water flow equations expressed by the matric flux potential that allows for depth dependent hydraulic conductivity variations in the upper layer.

Assouline et al. (2012) analyzed drip irrigation management techniques with different growing media and container media. Treatments with higher irrigation frequency or lower water applications rates showed increased water uptake rates by bell pepper, lower root mass, and smaller root mass/leaf area ratio. Comparison of various experiments showed a positive correlation between leaf area and root mass for bucket-grown plants while row grown plants revealed a negative correlation. To express the effects of growing media volume and hydraulic properties on plants they introduce the concept of mean daily available water volume per plant.

Scanlon and Kustas (2012) presented an evapotranspiration partitioning technique that combines measurements of eddy covariance flux with carbon dioxide fluxes. Resulting transpiration estimates were successfully employed to calculate canopy conductance. As canopy conductance is an important variable in land surface models, the presented evapotranspiration partitioning technique may aid the improvement of land surface models.

Durigon et al. (2012) compared two root water uptake reduction functions—the well-known Feddes reduction function and a function based on the matric flux potential—with data obtained from a field experiment with common bean. Simulations showed higher sensitivity to root length density distribution for the Feddes function. Root water uptake for the Feddes function showed smooth transitions in space and time, while the matric flux potential function showed concentrated uptake at a few depths, which was attributed to the sensitivity for hydraulic conditions. They noted it is necessary to include internal root resistance to improve root water uptake simulations with the matric flux potential function.

## Landscape Scale

Progressing along the hierarchy of evolving scales, three contributions to this special section addressed landscape-scale processes. As mentioned earlier, spatial variability is an attribute relevant at all scales of interest. There is a large body of literature dealing with spatial variations exhibited by model parameters, but more recently, studies about soil moisture variability are regaining their vigor thanks mostly to the availability of more reliable, relatively affordable soil water content sensors.

Guswa (2012) focused on creation of spatial variability in soil moisture by canopy interception and the subsequent homogenization by plant root water uptake. With coupled one-dimensional models forced by stochastic rainfall, he investigated root systems that vary in their ability to compensate for heterogeneous soil moisture and the resulting impact on the water balance and soil moisture variability. While the combined effects of canopy and root processes are at times offsetting, accounting for these processes is important to better represent hydrologic and biogeochemical processes at larger scales.

Soderberg et al. (2012) reviewed the measurement and modeling of stable isotopes in the water vapor of the vadose zone and related these to the implications for understanding SPAC at various scales. Recent development of laser-based isotope analysis facilitates in situ measurement of soil water isotopes. A case study of direct soil water vapor isotope measurements confirmed the generally assumed equilibrium between the soil liquid and vapor phase. These measurements were then used to improve the Craig–Gordon modeling framework that is commonly used to model the soil evaporation isotopic composition. Including the soil water potential into the Craig–Gordon modeling framework made the estimated fractionation for evaporation from unsaturated soils consistent with observations.

Time series of topsoil water contents and evapotranspiration fluxes have become available as a result of advances in remote sensing. The hydrological community is interested in determining how to make the best use of these datasets to identify effective hydraulic parameters and to simulate processes in SPAC. Pollacco and Mohanty (2012) proposed a methodology for reducing the nonuniqueness of the inverted hydraulic parameters using remotely sensed surface soil moisture and evapotranspiration. They investigated the uncertainties in simulating the water fluxes (e.g., evaporation, transpiration, groundwater recharge) of 18 contrasting hydroclimatic scenarios with a new uncertainty simulator algorithm. Results show that uncertainties in water flux increase as (i) climate becomes drier, (ii) texture becomes coarser, and (iii) roots grow deeper. For example, the uncertainty of recharge is explained by soil moisture and transpiration decoupling. Soil moisture decoupling occurs when the information provided by surface soil moisture is no longer representative of the root zone soil moisture due to strong evaporation. Transpiration decoupling occurs when there is substantially more water storage at depth with deep-rooted vegetation.

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