

Kirkham's Legacy and Contemporary Challenges in Soil Physics Research

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Don Kirkham was instrumental in transforming soil physics into a modern scientific discipline by developing theories based on verifiable hypotheses, creating methods to test the hypotheses, and applying the theories to problems of importance to society. We, the recipients of the Don and Betty Kirkham Award in Soil Physics, show how this legacy continues to affect soil physics. We describe eight longstanding or emerging research areas in soil physics that contain key unsolved problems. All are field oriented, with applications to a number of important issues in agriculture and the environment. The first three problems deal with the topic of characterization of field-scale soil water properties, within which we describe progress on scaling, effective hydraulic properties, and the relationship between soil structure and function. We then move to the description of unstable flow and characterizing water repellency, and finish with discussions on the effect of plants on transport processes, characterizing soil microbial diversity, and the importance of soil ecological infrastructure in providing ecosystem services. The challenges we discuss reflect inherent gaps between the complexity of the soil environment and its biogeochemical function, and the limited measurement and analytical tools at our disposal. Improving our predictive capabilities at relevant spatial and temporal scales will be necessary to address some of the long-standing problems within agriculture and the soil environment.

Don Kirkham was a true pioneer and innovator whose career as a teacher and scientist was instrumental in transforming soil physics into a rigorous discipline with a solid theoretical foundation. Inspired by his example and honored to have received the Don and Betty Kirkham Award in Soil Physics, we the co-authors found it appropriate to dedicate our contribution for the 75th anniversary issue of the Soil Science Society of America Journal to Don Kirkham's legacy, with a theme that he would have appreciated.

We describe research problems that we have worked on during our careers whose quantification and solution remain elusive. Some have been labored on for many years, while others have only recently emerged. All are field oriented, with applications to a number of important issues in agriculture and the environment. The first three problems deal with the topic of characterization of field-scale soil water properties, within which we describe progress on scaling, effective hydraulic properties, and the relationship between soil structure and function. We then move to the description of two important problems, unstable flow and water repellency, whose behavior violates the assumptions of our foundational Richards equation describing water flow in soil. We conclude with discussions of three emerging areas of research: the effect of plants on transport processes, the characterization of soil microbial diversity, and the importance of soil ecological infrastructure in providing ecosystem services.

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CHARACTERIZING TRANSPORT PROPERTIES IN FIELD SOIL

Problem 1: Development of Scaling Relations

The soil properties that influence the transport and retention of water and chemicals are difficult and time consuming to measure. Moreover, they vary considerably in space even across small distances in the natural environment. Our flow and transport models often require area- or volume-averaged estimates of these properties, yet the number of samples necessary to calculate meaningful averages at the field scale is often prohibitively large. Scaling relations were developed as a means to circumvent the measurement problem and to enable comparisons between similar systems by using one or more easily measured or estimated parameters to describe the differences in soil geometry from one region of soil to another. These parameters are then related to transport and retention properties through theoretical or empirical arguments, thereby allowing a set of properties measured at a given location to be extended to other regions via the regions' scaling factors.

Scaling Soil Heterogeneity

The simplest form of scaling is geometric similitude (Miller and Miller, 1956), in which all regions are regarded as structurally identical magnifications of a reference location, and a single scaling length λ_i (m) is all that is required to relate locations to each other. In this idealized medium, all locations have the same porosity and the local matric potential h_i (m) at water content θ is related to the reference matric potential h_{ref} at the same water content by the relation

$$h_i(\theta) = \frac{\lambda_{ref}}{\lambda_i} h_{ref}(\theta) \quad [1]$$

Similarly, the hydraulic conductivities K_i ($m\ s^{-1}$) of such a medium scale by

$$K_i(\theta) = \frac{\lambda_i^2}{\lambda_{ref}^2} K_{ref}(\theta) \quad [2]$$

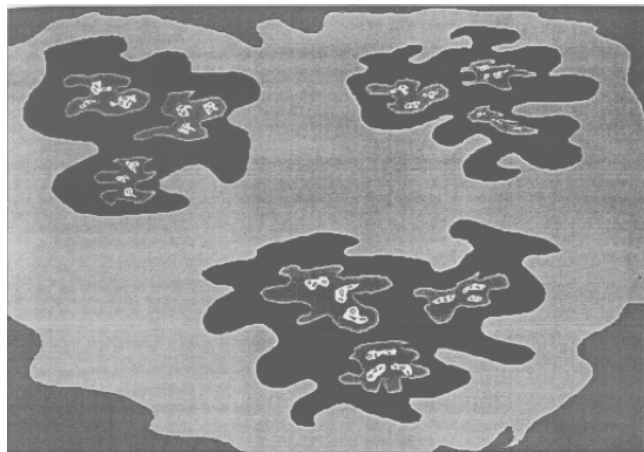


Fig. 1. Conceptual model of evolving soil heterogeneity (after Tyler and Wheatcraft, 1990).

Thus, if the complete set of hydraulic properties is measured at the reference location, then only the scaling lengths need to be known to calculate the hydraulic properties everywhere.

When tested under field conditions, the geometric similitude form of scaling theory proved inadequate at representing the heterogeneity of soil hydraulic properties. When separate scaling parameters were used for matric potential and for hydraulic conductivity, the variability was greatly reduced but not eliminated (Warrick et al., 1977). Further modifications, such as using relative saturation rather than water content, or using saturated hydraulic conductivity as a third scaling factor and scaling the relative hydraulic conductivity reduced the variability even more but at the price of requiring additional measurements at each location.

Pore and particle size distributions have proven to be useful for determining scaling factors. By assuming that the pore size distribution is lognormally distributed, Kosugi and Hopmans (1998) were able to use a physically based model to scale the soil water retention and unsaturated hydraulic conductivity functions. The scaled data both allowed the calculation of scaled-mean properties representing spatially averaged soil hydraulic functions and also characterized the spatial variability of the local properties. Recently, Nasta et al. (2009) successfully used the soil particle size distribution as the basis for scaling soil hydraulic properties after first dividing soils into groups of similar soil texture. Other researchers have utilized empirical relations for pore size distribution indexes of soil types to scale hydraulic properties across diverse soil series (Williams and Ahuja, 2003).

Upscaling

Scaling can also be used as a means of extending local measurements to larger soil volumes. An interesting implementation of this principle is the *scaleway* approach (Vogel and Roth, 2003), where the large-scale soil framework is represented as a multiscale pattern defined by a hierarchical and nested order of scales (Fig. 1). The structure at any scale is explicitly considered, while the finer scale heterogeneities are replaced by effective properties that may be represented statistically. To use the approach, a representation of the structure, a process model at the scale of interest, and the corresponding effective material properties must be known.

Fractal scaling models have been used to represent the soil water retention curve (Tyler and Wheatcraft, 1990) and to model the hydraulic conductivity (Gimenez et al., 1997), with the fractal dimension related to the pore size distribution. Analogous approaches have been developed using percolation theory (Hunt and Ewing, 2009). Whether these types of scaling would be applicable across a larger extent of scales than the limited range tested remains an open question.

We continue to be challenged by the task of applying physical, chemical, and biological principles derived or observed at small scales to the larger scales where they must be applied. For example, the Richards equation describing water flow has been tested only at small scales yet is increasingly being used to model significantly larger spatial scales in applications such as coupling

unsaturated flow with climate and groundwater models, hydrologic modeling of watersheds, and as a component of ecosystem modeling. There currently exists, however, no way to measure the boundary conditions, soil hydraulic functions, or vegetation information required to calibrate the model at this scale nor has it been demonstrated that such functions even exist. As a consequence, less complex conceptual models that do not require unsaturated soil hydraulic properties may be more appropriate at those scales, with soil hydraulic information inferred from indirect measurements such as remote sensing.

New instrumentation and techniques for measuring soil properties in situ are needed. Upscaling approaches are currently limited by our inability to measure soil hydraulic properties at a range of spatial scales and by inadequate representation of the heterogeneity of natural soil. Geophysical techniques, such as electrical resistance tomography and ground penetrating radar that sense soil dielectric and conductive properties throughout substantial soil volumes, may prove to be useful for inferring average soil hydraulic properties.

Multifractal modeling of soil structure shows promise in generating realistic hydraulic networks at fine scales, but significant additional effort is required to develop procedures for statistically characterizing and averaging across those structures to infer hydraulic properties at coarser scales. Inverse modeling can be applied to determine scale-dependent effective soil hydraulic properties across a wide range of spatial scales for which laboratory (soil core) and field experiments are available; however, the solutions obtained by this method may not always be unique. At larger spatial scales, remote sensing may be useful for developing relations between area-averaged quantities such as storage and drainage.

Problem 2: Defining Effective Properties

An effective property is a functional relationship between volume-averaged quantities and is scale and model dependent. Unsaturated hydraulic conductivity, $K(h)$, is an example of an effective property, defined as the ratio between the flux and the hydraulic potential gradient, all measured at the same scale. It has been shown to be monotonic and unique when the volume average is performed within a region of homogeneous porous materials. As the scale of averaging becomes larger and the material more heterogeneous, however, it is not guaranteed that a unique representation of this function will exist.

Hydraulic functions measured at the core or plot scale are notoriously variable in natural soil, with properties such as infiltration rate ranging across several orders of magnitude within a typical field (Sharma et al., 1980). Because the information required to create a continuous map of the variability of these properties is unobtainable, plot- and field-scale models of infiltration, soil water movement, and solute transport generally use average or “effective” soil hydraulic properties to represent the processes. Bresler and Dagan (1983) found, however, that effective average hydraulic properties within a heterogeneous volume cannot be derived that predict correct averaged outcomes for all conditions and processes. Moreover, changing the boundary or initial condi-

tions can sometimes produce different effective properties. Thus, it is important to obtain ways of defining and measuring effective properties that minimize errors in computing average flow and transport for a range of initial and boundary conditions.

Several investigators have developed methods for defining meaningful effective average properties under certain conditions. Feddes et al. (1993a) showed that inverse modeling and soil water content averaged from discrete measurements could be used to obtain effective properties that predicted the average water movement under dry to medium soil water conditions. In a companion study, they used area-averaged surface soil moisture and evaporation estimated from remote sensing to calculate the effective hydraulic properties for a large area by inverse modeling (Feddes et al., 1993b).

Zhu and Mohanty (2002) found that the geometric mean value of the Brooks–Corey (Brooks and Corey, 1964) bubbling pressure parameter and the arithmetic mean of the saturated hydraulic conductivity optimized the prediction of large-scale, steady-state evaporation and infiltration in a soil overlying shallow groundwater. The accuracy of the predictions depended on flow conditions and improved when the parameters were correlated, but the parameters defining the effective properties were different for evaporation and infiltration. Ahuja et al. (2010) computed the effective hydraulic properties for several different hypothetical soil compositions for rain infiltration and redistribution under 100-kPa initial suction. The effective properties obtained by matching the average early stage ponded-water infiltration of the component soils gave generally good results for infiltration up to 4 h for four rain intensities but failed to describe the observed soil water content distribution. To obtain acceptable results for both infiltration and redistribution, the effective saturated hydraulic conductivity obtained by infiltration matching had to be combined with the arithmetic means of the soil water retention parameters.

Future Directions

These studies and many others not mentioned show that the concept of an effective property averaged throughout a heterogeneous soil is a tenuous one that nonetheless may be useful under certain circumstances. At the present time, however, we are limited by a lack of understanding of a number of important relationships. For example, more data are needed describing the effect of varying rainfall intensities on effective hydraulic properties in a variety of heterogeneous soils to determine if a relationship exists between the effective properties and the average rainfall intensity. Similarly, additional effort is needed to evaluate the effect of different initial soil water conditions on effective properties for infiltration and redistribution in various soils and to study the interactions between the initial conditions and rainfall intensities.

We need to extend the concept of effective properties to layered soils having vertical as well as horizontal variability. It may be possible that in most cases infiltration is restricted to the top 30 cm and that the properties of the topsoil control infiltration and thus alone can define the effective properties. This simplification

is unlikely to work for redistribution, however, and it may be necessary to use the arithmetic or geometric mean properties of the combined layers to define the effective properties.

Problem 3: Relating Structure and Function Structure at Different Scales

Spatial organization in soils, usually referred to as soil structure, is present at all scales, and its influence on hydrologic processes is also scale dependent. At the pore or aggregate scale, soil structure is defined by the arrangement of minerals and organic matter in combination with biological components. At the horizon or pedon scale, soil structure appears as soil horizons and peds, which influence the retention and transport of infiltrating water and solutes, especially as preferential flow (Lin et al., 1999). At the field or hillslope scale, surface cover features control storage and partitioning between runoff and infiltration, thereby affecting groundwater recharge and ecosystem water (Zehe and Flüßler, 2001). Finally, at the watershed or basin scale, the spatial organization of soil types and associations along with the parent material provide information on soil cover structure, while soil-atmosphere interactions and feedbacks characterize the soil hydraulic functions emerging at this scale (Vereecken et al., 2010a). These features are best characterized using noninvasive or remote sensing methods, for example by computer tomography at the pore or aggregate scale, electrical resistivity tomography at the horizon or pedon scale, remote sensing vegetation imaging or ground penetrating radar at the field or hillslope scale, and topography-based soil landscape relationships at the watershed or basin scale.

At all scales, the critical unresolved issues are: the selection of parameters to characterize structure and hydraulic functioning, obtaining information about structure and function to find these parameters, and relating structure and function in a model using these parameters. Structural heterogeneity is extremely difficult to measure, and it is currently impractical to determine the precise location and properties of all relevant structural features of a soil at important scales of interest in soil management. Many soils possess discrete structural features such as cracks, channels, or macropores that occupy a relatively small part of the soil volume but can have a significant effect on transport and retention properties.

Structure Characterization Methods

One strategy that has been used to overcome this difficulty is to assume that the spatial void structure is random, which allows average water flow and retention properties to be inferred from a knowledge of the effect of structure on water behavior at the local scale, together with a statistical representation of the structure (Pachepsky et al., 2008). Several versions of this approach have been proposed for soils and other materials in the vadose zone. Functional evaluation, in which models whose parameters are calculated from pedotransfer functions are used to make specific predictions, has become a powerful tool for improving structure-function relationships (Wösten and van Genuchten, 1988). Because modern noninvasive methods can sense soil water con-

tent and flow as well as soil composition and structure, inverse modeling to find both parameters of structure and function from the same study is a promising new direction of research.

Future Directions

Simulations of flow and transport in synthetic structures having the same statistical properties as natural settings are invaluable for discovering and validating structure-function relationships. These efforts will require new tools such as geostatistical simulations or stochastic imaging to generate the synthetic structures accurately (Pachepsky and Acock, 1998). The description of hydrologic functioning will need to be advanced before we can parameterize hydrologic pathways that are opened above threshold values (Zehe et al., 2007).

Pedotransfer function techniques currently use only soil textural information to model hydraulic properties and would benefit greatly from the addition of structural parameters (Vereecken et al., 2010b). We need to develop ways of parameterizing structural indices obtained from noninvasive methods, however, because the data obtained from destructive sampling have proven to be only moderately useful (Rawls and Pachepsky, 2002).

Another possible approach to be developed in the future is to use structure characterization obtained by methods that sense the void space. An example is fusing data from field measurements of soil gas diffusivity (representing a soil structural fingerprint of connected soil pores drained at a given matric potential) and soil air permeability (a fingerprint of the larger, well-connected soil pores drained at a given matric potential) using state-of-the-art equipment (Hamamoto et al., 2009).

The commonly used Richards water flow equation and convective-dispersive solute transport equation models have limited applicability in structured soils where preferential flow is predominant, yet by default these models are used to infer soil hydraulic functioning even where their assumptions are not well met. Attempts are underway to develop structure-based screening of soil and soil cover to decide whether these classic models should be used (Jarvis et al., 2009).

Very little is known about how structure changes with time. We have some understanding of the effects of tillage and natural reconsolidation on the changes in soil hydraulic properties (Ahuja et al., 1998); however, we need to know much more about dynamic changes in void space in various structural units to be able to interpolate and extrapolate structure-function relationships in soil hydrology with time. Such temporal projections are needed to understand the changes in soil hydrology due to soil management and due to changes in ecosystems undergoing ecological succession or affected by climate change.

DEVIATIONS FROM SURFACE TENSION-VISCOUS FLOW

Problem 4: Unstable Water Flow in Soil

Research during the last half century has advanced our understanding of the conditions necessary for the onset of unstable flow in porous media, allowed us to characterize many of its fea-

tures, and enabled the development of specialized models of the phenomenon. There are many conditions in soil that allow instabilities to form and develop, including vertical flow from a fine-textured layer into a coarse one, vertical flow into a compressed air phase, infiltration into water-repellent soil, two-phase flow involving two fluids of contrasting density and viscosity, infiltration into homogeneous soil at flux rates substantially less than the saturated hydraulic conductivity, and redistribution following infiltration.

Conditions for Instability

Instabilities form when gravitational forces overcome viscous ones. A common instance where this occurs is when the matric potential decreases toward the surface during a flow event, such as during redistribution following infiltration. Once a finger forms and advances ahead of a wetting front into the dry soil below, it must be supplied by lateral flow of water from the surrounding wet soil matrix as well as from the region directly above the finger. In addition, downward flow of water and advance of the draining front in the matrix zone between fingers must greatly slow down so that water remains available for the finger. In order for these effects to occur, the dry soil region below the wetting front must have a threshold water-entry matric potential h_{we} (m) below which the wetting front will not advance.

Figure 2a shows a typical finger pattern observed in the laboratory, and Fig. 2b illustrates the formation and propagation of a finger during redistribution. During normal drainage, water pressure at the interface between the wet and dry zones is at the water-entry potential h_{we} , which allows water to enter the dry region below the entire draining front. As a perturbation forms, the depth of penetration becomes slightly greater at one point along the front, which shifts the local water pressure distribution downward and creates a local sink above the advancing finger. Subsequently, the water pressure in the surrounding matrix decreases, and the pressure at the wetting front may drop below h_{we} , thereby detaining the primary front and channeling water preferentially through propagating fingers until flow stops.

Modeling Unstable Flow Features

Description of the fingering process involves characterizing a number of processes and properties. Various attempts have been made to predict the finger diameter from soil properties and water flow characteristics. They either involve an approximate equation that is a function of the sorptivity (Parlange and Hill, 1976) or include a macroscopic surface tension associated with the large-scale curvature induced by the radius of the finger (Chuoke et al., 1959). A different approach was taken by Wang et al. (1998), who replaced the effective surface tension with an expression involving the water-entry pressure head h_{we} of the wetting curve by using the capillarity equation $\Delta P = 2\sigma/R$, where P is pressure and σ is the surface tension of water, and defining an effective macroscopic curvature R^* at the interface. They used empirical relations derived from laboratory studies for R^* and the area fraction. Observations of the fingering process have repeatedly shown that fingers remain narrow as they propa-

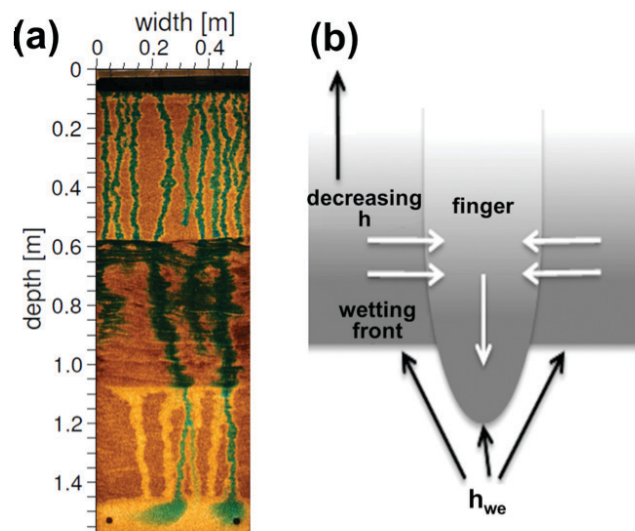


Fig. 2. (a) Flow instability observed by light transmission during water infiltration into layered medium, and (b) development of a fluid instability during redistribution, when capillary pressure h decreases toward the surface. When the front advances ahead at one location, the pressure distribution above it shifts downward, creating a lateral flow gradient from adjacent regions (Jury et al., 2003); h_{we} is the threshold water-entry matric potential below which the wetting front will not advance.

gate and persist for a long time after flow stops, which Glass et al. (1989a,b) showed was due to hysteresis in the matric potential water content function.

Predicting Unstable Flow

Although most of the effort to characterize fingered flow has been experimental, recent attempts have been made to model the transport process when fingers form and propagate. Because it has been shown that the classical Richards equation is unconditionally stable, even when hysteresis is included (Eliassi and Glass, 2001), some other formulation is needed to model unstable flow. The first class of models utilizes a nonequilibrium form of the pressure–water content relation together with hysteresis to generate unstable fingers that do not dissipate (Nieber et al., 2005). The second type of model is based on a pore network of pipes of variable diameter in which water propagates via invasion percolation (Flekkøy et al., 2002). Each formulation is capable of reproducing fingers that mirror experimentally observed behavior. More recently, a third type of model formulation has appeared in which the Richards equation has been modified to include an additional term to account for nonlocal effects associated with the extra energy required to displace air–water interfaces (Cueto-Felgueroso and Juanes, 2009). This new phase-field model turns the Richards equation into a fourth-order differential equation in space. These efforts represent important progress in extending the theory of water flow in porous media to the realm of unstable flow. Further progress is required to take these new models to the level where they might assist in assessing the degree to which flow in a soil with a given set of properties and

boundary conditions might exhibit instabilities and how such instabilities might propagate.

Unstable Flow during Redistribution

Many studies, whether experimental or theoretical, have focused on constant infiltration. From a practical standpoint, however, redistribution following infiltration has a much wider range of application because water application to the surface of a field soil is always intermittent. Moreover, redistribution is inherently unstable because it induces a negative pressure gradient toward the surface. Jury et al. (2003) used a conceptual model of fingering during redistribution that embodied known or postulated information about finger diameter and flow fraction to generate the final finger distributions as a function of soil properties. The principal conclusions drawn from this study were that unstable conditions in finer textured soils generated only wide fingers that moved negligible distances ahead of the draining front, whereas fingers in sandy soils could move substantial distances of more than a meter downward during redistribution following an infiltration of a few centimeters of water. They also noted that laboratory column studies of redistribution produce an artifact because the width of the column is typically too small to allow instabilities to form.

Characterizing Unstable Flow in Field Soil

Progress in this field has been rapid in recent years, but much work remains before we will have a tool for representing unstable flow in real soils. It will probably never be possible to predict the location where a finger will form because it may arise from small heterogeneities that are incapable of being characterized through prior measurement. Current theories contain parameters that cannot be determined experimentally; hence, additional effort is needed to describe such phenomena as effective surface tension, air-entry matric potential, hydraulic radius, and nonlocal free energy that appear in current formulations. No theoretical basis exists for predicting the area fraction active in fingering, and it must be estimated empirically. Finally, we have only a limited understanding of how important the consequences of unstable flow are. We do not know whether they are a near-surface phenomenon or whether instabilities will assist flow for substantial distances beneath the surface. We know next to nothing about the role of fingering in transporting solutes or how fingers interact with plant roots.

Problem 5: Characterizing Soil Water Repellency

When water does not bond to soil surfaces, the soil is deemed to be water repellent or hydrophobic. At the pore scale, water repellency alters the contact angle between the solid and liquid phases, which in turn reduces or eliminates the capillary forces stabilizing water in the soil. New measurement techniques have been developed to quantify the degree and persistence of water repellency, as well as to indicate its potential formation (Wessolek et al., 2009; Lamparter et al., 2010). These methods have greatly increased our knowledge of when and how water repellency occurs in soil. While fire-induced soil water repellency

has been an area of intense interest for some time (DeBano, 2000), repellency arising from other causes has been shown to be far more widespread than earlier believed.

We have some understanding of the interacting roles played by the soil's ecological infrastructure, that is, its porous architecture, its clays, its organic matter, and its microbial inhabitants. Water repellency has been found to affect each of the soil's ecosystem services, most particularly those relating to water and C, in both destructive and beneficial ways. Whereas Miyata et al. (2009) found that repellency caused an increase in runoff and soil erosion, Robinson et al. (2010) observed that the increase in preferential flow due to water repellency increased water sequestration under woodlands. Water repellency can also impact agriculture via the soil's provisioning ecosystem services for food and fiber production. For example, repellency-induced dry-patch syndrome in pastures in New Zealand can result in a 20 to 30% reduction in growth (M. Deurer, personal communication, 2010).

Modeling Water Repellency

From our observations of the impacts of repellency on soil ecosystem services, models of soil water repellency are being developed. These range from the functional (Dekker and Ritsema, 1994) through to the mechanistically complex (Bachmann et al., 2007). Despite these tools, however, we remain unable to predict when soil water repellency will occur, or disappear, and what impact these changed states might have on the regulating and provisioning of ecosystem services that are supported by soil functioning. Moreover, we do not know the spatial extent and temporal duration of either potential (measured on oven-dry samples) or actual (measured on wet samples) soil water repellency, nor why potential repellency is not always present, and why sometimes it can be "washed out" and not reappear. Our nescience is primarily because we do not understand the genesis of hydrophobicity at the pore-scale level.

Threshold Behavior

We are beginning to understand that a relatively small change in soil water content can have large impacts on soil water repellency. Once the soil becomes hydrophobic, it becomes highly likely that local-scale runoff and infiltration processes on or near the soil surface will initiate preferential flows in the soil's macropores above some critical water content (Dekker and Ritsema, 1994). We have limited ability to integrate our understanding of local processes, however, to predict what larger scale impacts on watershed hydrology might occur at the slope and catchment scale and on the regulating and provisioning ecosystem services across the landscape (Doerr et al., 2007). As C and water regulation, plus food provisioning, take on increased importance with climate change and population increases, it will be important to develop a better understanding of the role of water repellency in the supporting processes that soils provide.

The study of soil water repellency has primarily been the domain of soil physicists, (Dekker et al., 2005). Because repellency arises from a complex interaction between porous architecture, clay particles, soil organic matter, and microbial pro-

cesses, and because hydrophobicity has landscape-wide impacts on the regulating and provisioning services supported by soil, it is imperative that a multidisciplinary approach be adopted. At the fundamental level, this will require physicists to work closely with chemists, biologists, and mycologists. At the large scale, agronomists, ecologists, and resource economists need to integrate this better understanding of water repellency into farm-scale and landscape modeling.

Measurement Needs

Despite recent progress, we are still in urgent need of better measurement techniques. We need better information on the active parts of the soil's organic matter, on the coating mechanisms that create hydrophobicity on mineral surfaces, and how these micro-effects scale up to the aggregates that comprise the soil's porous matrix. New scanning technologies such as nuclear magnetic resonance and near-infrared spectroscopy will probably help us in this quest, as will investigations using different liquids to assess the degree of hydrophobicity. Presently, our standard methods to quantify water repellency only work within a limited range of contact angles, from about 50 to 110°. New tomographic scanning technologies, along with proximal and remote sensing techniques, will allow us to observe the impact of repellency at both the local and larger scales of soil functioning.

We must improve the modeling of water-repellency dynamics, as well as its impact on the soil's ecosystem services. Our models are either too simple to handle complexity (Dekker and Ritsema, 1994) or too complex to be useful (Deurer and Bachmann, 2007). With better knowledge and improved prediction tools, we can develop strategies to reduce the ecosystem disservices generated by soil water repellency while enhancing the supporting soil services that are reliant on hydrophobicity. This could involve modifying the soil's ecological infrastructure to achieve the sought-after ecosystem services through vegetation and grazing management, by manipulating the soil's microbiology, or by land imprinting, as well as through the addition of soil amendments and the use of natural surfactants.

INCORPORATING THE BIOLOGICAL COMPONENTS OF SOIL

Problem 6: Flow and Transport in the Soil–Plant Continuum

Our understanding of dynamic processes in the soil–plant continuum has greatly progressed in recent years due to the development of novel measurement technologies combined with increasing capabilities and progress in numerical modeling. For all of this progress, however, we are still at the early stages of understanding how to describe the many processes influencing flow and transport when plants are present.

Modeling Root Water Uptake

It is now generally accepted that water uptake by roots can be described by a composite transport model consisting of three major pathways: (i) the apoplastic path, which is the free diffu-

sional space outside the plasma membrane; (ii) the symplastic path, which is the inner side of the plasma membrane in which water and low-molecular-weight solutes can freely diffuse; and (iii) the transcellular path, which is movement through cells (Steudle and Peterson, 1998). In addition, water uptake can be regulated through the existence of water channels or aquaporins (Steudle, 2000). These various pathways are typically lumped together in flow models using an approach based on Ohm's law, consisting of an effective root resistance and a pressure head gradient between the soil and the root compartment.

Current water uptake models either describe the process explicitly at the scale of a single root or use a large-scale sink term. Microscopic-scale models typically calculate water and nutrient fluxes from the soil into the root system based on local flow laws. Root representation has evolved from simple root geometry models involving root length density toward more complex models considering three-dimensional dynamic root architectures embedded in heterogeneous, three-dimensional, variably saturated soil systems that solve for both the root and soil water potentials.

Macroscopic-scale models assume that root water uptake is proportional to the root length density and that uptake is locally reduced depending on the soil saturation or salinity (Šimůnek and Hopmans, 2009). This approach does not require information about root geometry and flow paths because it represents the water uptake process in a single macroscopic term that is included in the soil water balance. Macroscopic models are designed to be applied at the field and plot scales, but identification of their parameters from experiments has proven to be difficult if not impossible (Vrugt et al., 2001). Moreover, their parameters are site specific, and models calibrated at one location cannot be used elsewhere. At the present time, microscopic models can only be applied at the scale of one or a few plants due to the large data requirements and computational costs in the numerical solution of the governing equations.

Most of the macroscopic modeling approaches rely on one-dimensional root density profiles, neglecting the complete root architecture. Water and nutrient uptake depend on the location within the root system, however, and may vary in space and time by an order of magnitude (Pierret et al., 2007). Roots may develop root hairs to increase the area of soil exploitable by the plant and also to increase plant stability (Gilroy and Jones, 2000). Large changes in physiological properties may occur along roots as a result of aging and differentiation (Hodge et al., 2009).

Nutrient Uptake by Plant Roots

The driving force for most solute uptake is the electrochemical gradient across the root plasma membrane, a major portion of which is generated by H-ATPase (Glass, 2009). Some nutrients may diffuse passively into the root system via this electrochemical gradient (e.g., Ca^{2+}), whereas an uptake mechanism requiring the activation of specific transport pathways is required for other nutrients (e.g., NO_3^- or PO_4^{3-}). The transport pathways used by nutrients therefore depend on the type of nutrient, the

soil solution conditions, and environmental factors controlling the plant demand for nutrients and water. Because active uptake processes may differ significantly among ions and plant species, current model approaches that are based on supply-driven Michaelis–Menten kinetics do not capture the full complexity of nutrient uptake processes, in particular the dependence of affinity as a function of soil ion concentration (Roose et al., 2001).

More sophisticated approaches that consider the dynamic character of nutrient uptake parameters and more complex uptake kinetics need to be developed. Some studies have suggested that plant regulation is the dominant factor in nutrient uptake and that uptake is demand driven (de Willigen, 1987). The interaction between the above- and belowground parts of the plant system and their relation to root dynamics and water and nutrient uptake processes has been neglected (Hodge et al., 2009) and is critical to the further development of our understanding of water and nutrient uptake. This implies that the nutrient requirements of the plant and its distribution between root and shoot may need to be modeled as well as conditions within the soil. Nutrient uptake may also be facilitated by the release of water by roots in dry zones based on the concept of hydraulic lift used by plants to transport water from deeper soil layers to upper drier layers during the night (Caldwell et al., 1998).

The interaction between water uptake and nutrient uptake also requires further research because the flow of each can alter the forces driving the other across root surfaces. At present, root water and nutrient uptake models do not consider interactions between the two processes. These interactions might be very important in the case of the adaptation of plants to stresses such as drought, salinity, and toxic substances (Hopmans and Bristow, 2002).

Root–Soil Coupling and Feedback Mechanisms

There are complex interactions and feedback mechanisms between roots and soil, which typically take place in the rhizosphere. Roots release chemicals such as organic anions, protons, or enzymes to facilitate the acquisition of nutrients by changing the pH or redox conditions. Mucilage exuded by roots can modify water retention in the rhizosphere compared with that of the surrounding bulk soil water (Carminati et al., 2010). Accounting for numerous chemically induced processes would require the integration of biogeochemical reaction processes into soil–plant interaction models (Hinsinger et al., 2009). Up to now, only a few models have considered the effect of roots on the surrounding soil environment (e.g., Szegedi et al., 2008).

Root architecture development is determined by both biotic and abiotic factors in the soil profile and the aboveground part of the plant (Pierret et al., 2007). For example, there is evidence that a heterogeneous distribution of nutrients may lead to the proliferation of roots into zones of higher nutrient concentration. The roots of vines and citrus trees, through hormonal signaling from dry soil root zone regions to wet root zone regions, can enable the plant to adopt water conservation strategies that reduce the amount of irrigation water needed (Dirksen et al., 1979). Stress conditions, such as a lack of nutrients and water

shortage, lead to reallocation of assimilates from the shoot to the root to optimize the acquisition of water and nutrients by growing more roots in the wet or nutrient-rich areas of the soil. This indicates that there are complex feedback mechanisms acting in the soil–root–plant system that are controlled by external conditions requiring further research before models of the process can be developed (Teuling et al., 2006).

Root conductivity may vary in response to external stress or internal factors such as the nutritional state and water status of the plant (Steudle, 2000). Measured uptake rates of NO_3^- and water suggest that only 10 and 30%, respectively, of the total root length system is involved in both processes (Hodge et al., 2009). In addition, root systems may react to the soil environment by proliferating into nutrient-rich patches or by retreating from regions of the soil that are devoid of water or nutrients by letting the root mass die off. Research is needed to improve our understanding of xylem hydraulics, including the extent and mechanisms of hysteresis in xylem transport due to cavitation and a mechanistic understanding of the regulation of the plant water status due to stomatal control. An improved understanding of xylem dynamics is needed to obtain a mechanistic link between soil water availability and canopy water use (Sperry et al., 2003).

Large-Scale Modeling of Root Water Uptake

At larger scales, most of the root water uptake models used in land surface descriptions are empirical and are not able to describe important processes such as the effect of various stress factors on water and nutrient uptake. Recently, Ostle et al. (2009) pointed out that predictions of the biogeochemical cycles of water, N, and C made with various dynamic global vegetation models may contrast considerably due to differing assumptions about key soil–plant interaction processes at the local scale. Improved description of local-scale soil–plant interactions in combination with identification of the key processes and feedback mechanisms may therefore contribute to an improved prediction of global biogeochemical cycles.

New Research Opportunities

Improving our understanding of soil–plant interactions will require well-designed experiments at the laboratory, plot, and field scales. Early stress recognition of plant stands has become possible due to the development of novel measurement techniques such as hyperspectral sensors operated at the plant stand, fluorescence, and isotopic techniques. Imaging methods based on magnetic resonance imaging (MRI), neutron tomography (NT), and electrical resistance tomography (ERT) have allowed more precise laboratory- and lysimeter-scale experimental studies of soil–root water uptake processes to be conducted, resolving for the first time the spatial and temporal dynamics of the soil water distribution from the micrometer scale (MRI and NT) up to the 0.1-m scale (ERT combined with lysimeter experiments) (see Fig. 3). In addition, new tensiometer systems will allow measurements of pressure head values in regions beyond the permanent wilting point.

Problem 7: Physical and Ecological Origins of Soil Microbial Diversity

Factors Affecting Diversity

By some accounts, exploring the soil microbial diversity represents a scientific frontier at a scope similar to that of space exploration. Curtis and Sloan (2005) stated, "...there are 10^9 times more bacteria on Earth than there are stars in the Universe ... an immense and unexplored frontier in science of astronomical dimensions and of astonishing complexity." The high degree of microbial diversity found in soil is a consequence of the many complex pore surfaces and spaces housing dynamic aqueous and chemical microenvironments that may separate bacteria spatially, physiologically, or genetically. Because soil is far from being well mixed, spatial heterogeneity in aquatic habitats and the availability of nutrients such as C can arise and persist. Plant-derived material, the main source of soil C, is transported from the soil surface to deeper layers via the action of soil macro- and micro-biota and, most importantly, by transport with water. Water flow in soil is not homogeneous, and preferential flow pathways may form hot spots characterized by a higher water-soluble C concentration than the adjacent soil matrix (Bundt et al., 2001).

The dynamics and spatial arrangement of water are particularly important for soil bacteria. Temporal and spatial variations in the amount and configuration of water in soil pores results in a flickering aqueous network that shapes diffusional pathways for nutrients and promotes or suppresses mobility and connections between soil microbial communities even across very short distances (Mills, 2003; Or et al., 2007). Although heterogeneity and microhabitat fragmentation are often cited as factors promoting the immense soil microbial diversity, the study and modeling of the key factors sustaining diversity are in their infancy.

Diversity and Scale

The physical processes that control soil microbial habitats, community diversity, and activity may vary with spatial scales. Diffusional limitations may dominate at the pore scale, limiting interaction among microbial colonies with length scales of the order of 10 to 1000 μm . Even at this microscale, heterogeneous diffusional pathways and aquatic habitat fragmentation may support microbial coexistence and lead to the microbial diversity observed in soils (Torsvik and Ovreas, 2008). At the sample scale of 10 to 100 mm, convective transport becomes prominent, forming nutrient gradients and supporting "hot spots," or regions with elevated microbial activity such as the rhizosphere (Bundt et al., 2001). Continuum representation of gaseous fluxes and exchange with the atmosphere becomes meaningful at the sample scale (Skopp et al., 1990). Quantitative models for microbial transport through soils focus on processes at the sample and profile scale, often combining convective-dispersive transport with elements of filtration theory to describe interactions with soil surfaces (e.g., Hornberger et al., 1992).

Soil formation processes result in differences in soil materials that in turn affect transport properties and microbial activity at scales of soil layers (0.1 m) to the soil profile or pedon scale

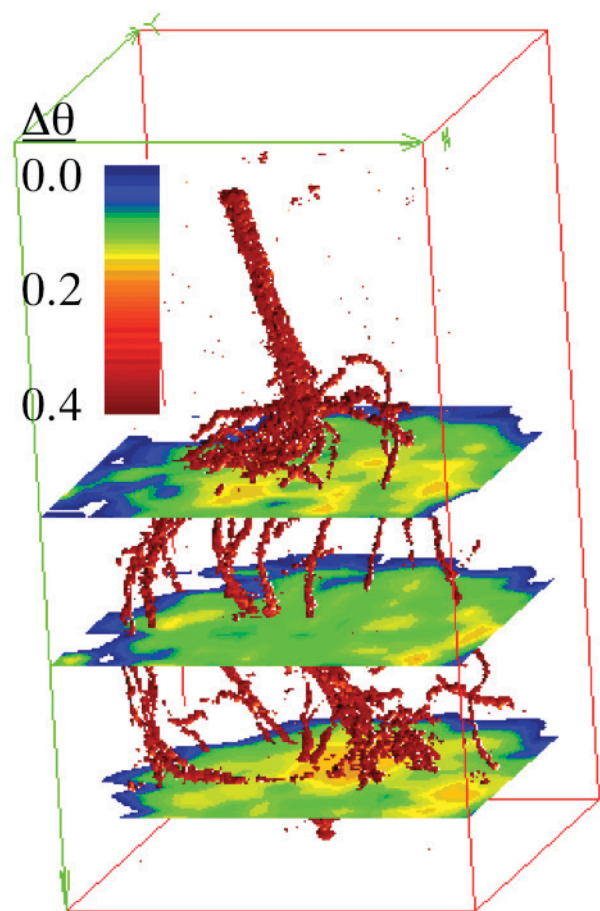


Fig. 3. Three-dimensional root architecture (brown) and water content changes, $\Delta\theta$, of a *Ricinus* plant grown in sandy soil during a period of 20 d after initial saturation. Original resolution of the magnetic resonance image is 0.6 mm for the root system and 6.3 mm for the water content (from Pohlmeier et al., 2008).

(~ 10 m). Differences in soil texture and organic C content between layers affect long-term wetness and aeration conditions as well as nutrient and gaseous fluxes, resulting in gradients in microbial abundance and composition (Kreft et al., 1998). Nutrient diffusion and microbial migration typically do not exceed the pedon scale, giving rise to noninteracting microbial populations. The primary interactions at these scales are via convective transport pathways (soil macropores and fractures) and plant roots.

Wang and Or (2010) used a model to demonstrate how capillarity and water films constrain bacterial motility and colony growth on partially hydrated rough surfaces (Fig. 4). Subsequent simulations and experiments on rough (capillary) surfaces demonstrated that bacterial motility confers ecological advantage only within a surprisingly narrow range of hydration conditions and that there is no difference in the expansion rates of motile and nonmotile bacteria at matric potential values lower than -5 kPa. Subsequent studies illustrated that drier and more heterogeneous rough surfaces promote and prolong the coexistence of two competing bacterial species (Zhou et al., 2002).

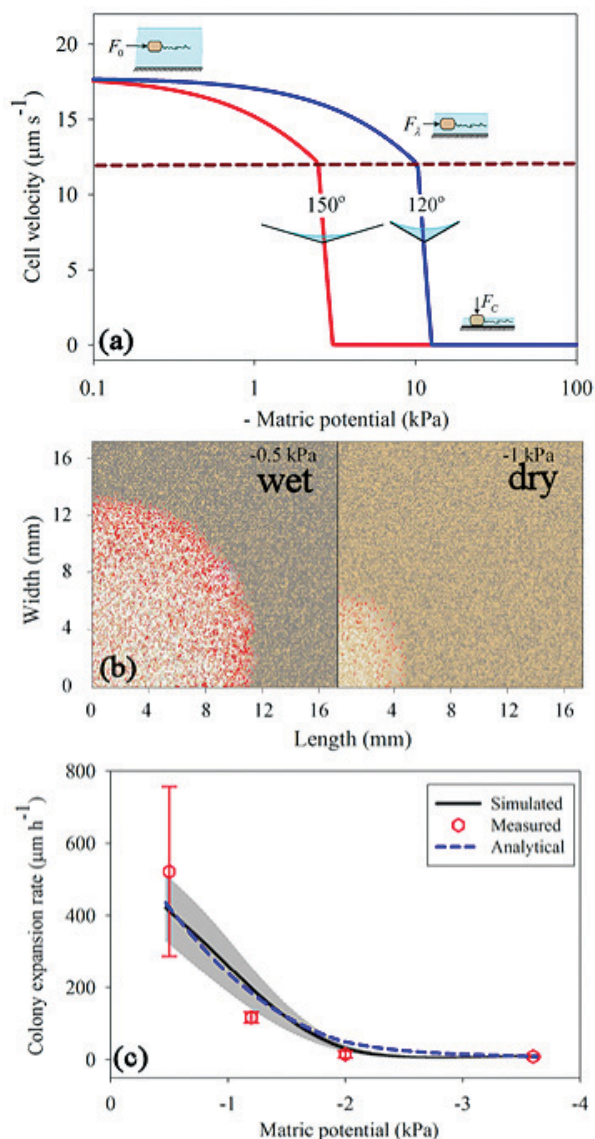


Fig. 4. Effects of hydration status (matric potential) on bacteria motility and colony expansion on simulated rough surface: (a) simulated bacterial cell velocities as a function of matric potential with V-shaped bonds with two spanning angles and similar bond depth (100 mm), where the dashed line marks critical water film thickness (equal cell diameter) with F_0 , F_s , and F_c the viscous drag force opposing motion in bulk water, the cell-surface interactions force, and the capillary pinning force, respectively; (b) simulated microbial colony patterns 25 h after inoculation on “wet” and “dry” rough surfaces; and (c) comparison of numerical and analytical models with measurements (Dechesne et al., 2008) of colony expansion rates as a function of matric potential (Wang and Or, 2010).

Microhydrology and Bacterial Survival Strategies

The narrow range of hydration conditions sustaining bacterial motility in soil pores suggests that colonization of new surfaces and dispersion of soil microbial populations is limited to short time windows when the soil water content is near saturation. The range of water potentials (and relative humidity, RH) supporting the growth and activity of microbial life is also relatively narrow; at 99% RH, microbial growth becomes limited and at a water potential of -5 MPa (RH $\sim 96\%$) bacterial respiration ceases (Potts, 1994). Under extreme desiccation con-

ditions, the primary survival strategy is for microorganisms to completely abolish their metabolism and switch into a dormant state (Torsvik and Ovreas, 2008). Accounting for these limitations is vital to improving the modeling of bacterial transport in unsaturated soil and to understanding the links between microhydrology dynamics and the functionality of species having different survival and reactivation strategies.

Microbes respond to local hydration fluctuations by biosynthesizing extracellular polymeric substances (EPS) surrounding their cells, which also facilitate colonies sticking to solid surfaces. Aggregation and pooling of resources as a defense against variations in hydration status and in nutrient availability enhance cooperative genetic and metabolic exchanges. The ubiquity of microbially excreted EPS across many different environmental conditions and habitats is attributed to its key role in environmental adaptation, in particular anchoring, nutrient entrapment, and the maintenance of favorable hydration conditions (Roberson and Firestone, 1992). The EPS support higher water retention and consequently higher nutrient diffusion rates within EPS-rich microenvironments relative to the surrounding soil under dry conditions.

The need to formulate quantitative links between hydrologic processes and microbial life in the soil is motivated both by fundamental ecological questions related to diversity and its maintenance as well as by practical environmental, agronomical, and engineering questions, for example, issues related to the introduction and stimulation of bacteria for remediation activities in the soil or the prediction of bacterially mediated nutrient cycles and gaseous fluxes at all scales. The environmental impact of the ongoing molecular revolution with rapid advances in the identification and unraveling of complex functions of microbial populations would be significantly enhanced when placed in the proper hydrologic and porous media context. That is an interdisciplinary frontier where soil physics can play an important role.

SOILS AS A COMPONENT OF ECOSYSTEMS

Problem 8: Soils, Ecological Infrastructure, and Ecosystem Services

Soils are often mismanaged because we pay little attention to their role as key components of “ecological infrastructure.” This neglect is due to the fact that we have no adequate means of properly quantifying the natural capital value of soil. Natural capital comprises the stocks of natural materials and energy (Costanza et al., 1997). Ecological infrastructure (EI) (Bristow et al., 2010) can be broadly defined as the underlying framework of natural elements, ecosystems, and functions and processes that are spatially and temporally interconnected to maintain the continued regeneration and evolution of life on Earth. Explicitly, the EI is how natural capital stocks are organized to produce ecosystem goods and services.

Ecosystem goods, such as minerals, foods, fibers, and fuels, can be easily valued because they provide quantifiable benefits in terms of economic markets. As yet, however, we do not have a complete understanding of the value of all natural processes, including those necessary for human life. Soils provide many raw materials, includ-

ing the provisioning of food, fuel, and fiber for humans, plus habitat and refugia for flora and fauna. Soils play a vital role in filtering nutrients and contaminants, detoxification and decomposition of wastes, storage of C, water, and N, plus the control and regulation of pests and diseases (Dominati et al., 2010).

In a landmark study, Costanza et al. (1997) estimated the global value of ecosystem services to be \$US33 trillion. Attempts have been made to value the services provided by soils (e.g., Clothier et al., 2008), but we are still struggling to develop a framework that would enable the total value of the soil's natural capital to be accurately determined.

Despite its increasing adoption in science and policy, the ecosystems services approach cannot cope with the complexity and interconnectedness of natural systems because it is very difficult to isolate, quantify, and thus value all the natural processes involved in the provision of a given service. It is important to identify and value various ecosystem services before we inadvertently, or even knowingly, lose them, but there is an even greater and more urgent need to understand and invest in the EI that underpins all natural processes (Bristow et al., 2010). One of the key elements of EI is the soil, which provides a great number of goods and services (Clothier et al., 2008). While the nature and values of some soil services are still unclear, what is becoming clearer is that there needs to be more comprehensive investment in both understanding and maintaining the integrity of the underlying soil infrastructure that delivers these critical services (Bristow et al., 2010).

Land and water management provides opportunities, and risks, to change certain soil properties, and thereby exerts influence on various soil processes such as hydrophobicity. This then affects the soil's service delivery for the filtering and buffering of water and food provisioning, either from a service perspective (Robinson et al., 2010) or via disservices (Deurer and Bachmann, 2007) (see water repellency discussion above).

Soil scientists and economists currently have no common language with which to communicate, and this has inhibited their mutual engagement with decision makers and the public (Dominati et al., 2010; Robinson and Lebron, 2010). The concepts of EI and ecosystem services lay the foundation for a solution to this dilemma.

We cannot spatially, or temporally, isolate the value of soils and their natural processes from the EI because soils are the substrate on which plant and animal ecosystems thrive. They are the matrix through which water, energy, gases, and chemicals flow. There is an urgent need to increase our understanding of (i) the connectivity of the EI elements and the ecosystems that comprise the EI, (ii) the impacts of land uses on EI and how they affect the provision of ecosystem services, (iii) the connection between EI and built infrastructure (BI), and (iv) how to better design and operate the BI so it is more in tune with the EI.

Soils should be treated as a key component of an interconnected EI and linked to the BI. Just like our continuing investment in the BI, which includes roads, power lines, and dams, we need to ensure investment in restoring, maintaining, and

enhancing the integrity and functioning of the EI, including the soil infrastructure. This will require coordinated approaches and will involve a wide range of scientific disciplines, from soil physicists through to ecologists and economists.

It will also require an "ecological focus" as opposed to simply an "economic focus," and the development of knowledge that accounts for the interconnectivity and overall functioning of the EI. This is not possible using the existing suite of economic and nonmarket valuations and scientific tools. Until a truly transdisciplinary engagement occurs, we will continue to treat soil like dirt and future generations will pay the price for a lack of investment in EI.

SUMMARY AND OUTLOOK

Any discussion of the key challenges facing contemporary (and future) soil physics research would be incomplete without addressing links with key societal issues dominated by global change, food security, and diminishing soil and water resources. The challenges discussed here reflect inherent gaps between the complexity of the soil environment and its biogeochemical function, and the limited measurement and analytical tools at our disposal. Improving our predictive capabilities at relevant spatial and temporal scales is necessary to address some of the long-standing problems within agriculture and the soil environment. Nevertheless, as members of the soil and earth science communities, we need to become more engaged in seeking solutions to global issues of resource scarcity and environmental degradation that require multidisciplinary effort. We have listed some of the research areas impacting global issues where soil physics (and soil science) could make important contributions, such as characterizing plant–soil interactions in the hydrologic cycle and food production, and valuing and preserving the soil's ecological infrastructure and associated ecosystem services. The future visibility and vitality of our discipline will be greatly enhanced if we play a more prominent role in solving the big problems impacting the planet by providing input to climate modelers, resource planners, and policymakers.

For motivation, Don Kirkham kept a note taped to his desk that read 'keep moving' on the challenging problems identified in this paper.

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