Special Section: Soil as Complex Systems

Core Ideas

- Complex soil systems are arenas of enormous variety of interactions between physical, geochemical, and biological processes.
- The system complexity may arise from interactions between the system's constituents.
- Soil systems are not simply complicated, but fall under the definition of a complex system.

Preface to the Special Issue of *Vadose Zone Journal* on Soil as Complex Systems

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This special issue of the *Vadose Zone Journal* entitled "Soil as Complex Systems" is a product of the first Complex Soil Systems Conference, "A Path to Improved Understanding of Complex Soil Systems," (http://esd1.lbl.gov/research/programs/ERWR/soils_conference/, accessed 22 Jan. 2016) hosted by the Earth Sciences Division (ESD) of Lawrence Berkeley National Laboratory (LBNL) from 3–5 September, 2014, in Berkeley, CA. More than 170 scientists from 13 countries attended the conference, representing many scientific disciplines—including ecology, hydrology, geophysics, agriculture, soil chemistry, soil physics, soil microbiology, mathematics, and modeling of soil–climate interactions. More than 120 abstracts were submitted to the conference and published in the Conference Proceedings. The Conference was supported by SSSA Bouyoucos funds, the Berkeley Lab, the USDOE, MoBio Laboratories, Inc., private donors, as well as several in-kind sponsors, including the *Vadose Zone Journal*. The cross-disciplinary nature of the conference program and discussions were unusual, even for soil conferences—perhaps underscoring the forthcoming paradigm shift in how scientists must approach the study of soils by bridging gaps in current scientific knowledge via addressing soil science fundamentals. The conference highlighted the importance of developing new measurement tools, models, and approaches, and methods to illuminate critical interactions and feedbacks between all components of the soil systems as needed for the development of sustainable solutions for agriculture, soil and groundwater remediation, and responses to climate change challenges.

Complex soil systems are arenas of enormous variety of interactions between physical, geochemical, and biological processes. The study of complex systems is a relatively unexplored area of science. A central concept in complex systems is that the dynamics of the system can exhibit complexity not built into the laws governing individual behavior, but which "emerges" from a relatively simple set of interactions between the constituents. Some authors have called such study "a new scientific discipline," but it may also be understood as discovering aspects in our existing science that were always present, but not perceived clearly. Complex soil systems display characteristics of open thermodynamic systems such as multiscale interactions and coupling, positive and negative feedbacks, nonlinear dynamics, emergence, and a sensitive dependence on initial conditions. In recent years, the necessity and urgency of cross-disciplinary expertise for improved understanding of soil system functioning and for improvement and integration of observational, experimental, and modeling methods and data paired with soil systems theory (e.g., USDOE, 2010) has become evident. It is also evident that we need to provide a galvanizing agenda to focus on improving understanding of complex soil systems—this is especially important given the critical role that soils play in sustaining life, including agriculture, water resources, and nutrient cycling.

The current issue of the *Vadose Zone Journal* includes several papers presented at the conference and also papers submitted in response to the call for papers for the special issue of the journal.

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Papers submitted to this special issue follow several themes. The first theme focuses on fundamental concepts of complex soil systems and how soil physical, chemical, and biological components and processes influence the soil–plant–atmosphere system at multiple spatial and temporal scales.

Dupuy and Silk (2016) described the mathematical framework for analyzing processes involved in colonization of root tips, including root growth kinematics. The authors found that the root elongation rate and bacterial attachment rate are factors that affect exposure of microbes to root exudates and are key to successful colonization of the root tip. Microbial attachment to roots contributes to dispersion of microbes in soil and to synergistic–antagonistic interactions between microbe and plant biochemistry. Also, the root cap may play a role in the maintenance of symbiotic bacteria at the tip.

In the second theme, the authors report on advances in soil characterization and experimentation, specifically on quantifying critical in situ soil processes using genomic, synchrotron, isotopic and field biogeophysical techniques. Here, Ding et al. (2016) used measurements of noble gas transport in a laboratory column experiment to test current theoretical models. The agreement between experiments and models demonstrates the potential of noble gas measurements to understand key attribute of natural systems, including porosity, tortuosity, and gas saturation. Yakubova et al. (2016) reported on the development of mobile inelastic neutron scattering system capable of routine soil carbon measurements. The authors determined that the average carbon weight percent in the upper soil layer could be determined for any carbon depth profile by in situ inelastic neutron scattering measurement for an hour. The new method of data processing removes system background and yields results that agree with the dry combustion method.

The third theme is focused on conceptual, theoretical, and numerical models to describe and predict soil systems behavior. Approaches include the use of linear and nonlinear dynamical models, stochastic, deterministic, and deterministic-chaotic modeling approaches, self-organizing and emergent processes. In one contribution, Hunt (2016) applies percolation theory to describe solute transport in porous media. In particular, the author provided an example where hierarchical root structures of vascular plants enable roots to exploit nutrients at more rapid rates than abiotic transport processes, with percolation theory predicting their growth rates out to 100,000 yr. Hunt (2016) shows examples of the two predicted scaling functions, both of which are proportional to the typical subsurface flow velocity, a rate, which limits crop growth. In another contribution, Nimmo (2016) presented a model for preferential flow in macropores based on the short-range spatial distribution of soil matrix infiltrability

Germann and Karlen (2016) presented the development of a fundamental theory of infiltration based on the viscous-flow approach. Ghanbarian and Daigle (2016) numerically simulated fluid flow in binary mixtures of low and high-permeability components in porous media constructed of spheres and ellipsoids using the lattice–Boltzmann method. They applied the effective-medium approximation to predict permeability in the simulated binary mixtures and showed the validity of this approach. Wilson et al. (2016) used the multifractal approach to characterize changes in inner structure, heterogeneity, and evenness of penetration resistance vertical profiles over a period with increasing soil water deficit.

The focus of the fourth theme is on soil systems and climate change, especially how integrated observations, models, and case studies document the feedback between soil processes and global climate change at spatial and temporal scales. Carminati et al. (2016) showed that the fraction of the rhizodeposits referred to as mucilage plays a crucial role in soil–plant water relations, even increasing tolerance of plants to drought. Liu et al. (2016) proposed a hybrid, reduced-order model that efficiently predicts fine-resolution responses to forcing by first training the algorithm with solutions from a computationally intensive model. The method was applied to sites being studied in the "Next-Generation Ecosystem Experiments-Arctic" program, to predict fine-resolution soil-moisture fields based on precipitation and evapotranspiration rates.

The fifth theme addresses practical applications, including those from managed and unmanaged systems. Schulz et al. (2016) extended the known realm of upland mottling and showed that such features can be important in upland unsaturated soils. Specifically, a suite of complementary analyses suggests that deep soil horizons on old stable landforms can develop reticulate mottling as the long-term imprint of rhizospheric processes.

Concluding Notes

A recognition that soil systems are not simply complicated, but rather fall under the definition of a complex system implies that conventional deterministic soil and hydrologic experimental methods and models are not adequate for developing a predictive understanding of complex soil systems, now or under near future conditions, but also indicates availability of alternative approaches to understanding such systems. New approaches are needed to quantify the physical, chemical, and biological processes taking place in soil and to predict the role of fine-scale physical, chemical, and biological heterogeneities on larger scale soil system hydrological and biogeochemical behavior.

Currently there is no broad understanding of necessary and sufficient fundamentals to use the complex systems approach for soil sciences, despite the many publications containing individual components of complex systems theory, such as fractals, networks, or chaos models. Moreover, the majority of publications often focus on minor, heterogeneous, or independent variables, with no emphasis on their relative importance or correlation with other variables. Thus, there is no general theory in the field of complex soil systems. We would like to add to this that, as always in the field of applied sciences, the theoretical foundations require careful hypothesis testing and verification. Many of the Bouyoucos Conference papers were devoted to experimental studies, and an objective of the organizers was to begin to move soil science in the direction of dealing with "complexity," which is an intriguing intellectual challenge that applies to *our* real world

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References

USDOE. 2010. Complex system science for subsurface fate and transport. DOE/SC-0123. http://doesbr.org/complexityreport/Subsurface_complexity_03_05_10.pdf (accessed 22 Jan. 2015).

Carminati, A., E. Kroener, M.A. Ahmed, M. Zarebanadkouki, M. Holz, and T. Ghezzehei. 2016. Water for carbon, carbon for water. Vadose Zone J. 15(2). doi:10.2136/vzj2015.04.0060

Ding, X., B.M. Kennedy, W.C. Evans, and D.A. Stonestrom. 2016. Experimental studies and model analysis of noble gas fractionation in porous media. Vadose Zone J. 15(2). doi:10.2136/vzj2015.06.0095

Dupuy, L.X., and W.K. Silk. 2016. Mechanisms of early microbial establishment on growing root surfaces. Vadose Zone J. 15(2). doi:10.2136/vzj2015.06.0094

Germann, P.F., and M. Karlen. 2016. Viscous-flow approach to in situ infiltration and in vitro saturated hydraulic conductivity determination. Vadose Zone J. 15(2). doi:10.2136/vzj2015.05.0065

Ghanbarian, B., and H. Daigle. 2016. Permeability in two-component porous media: Effective-medium approximation compared with lattice-Boltzmann simulations. Vadose Zone J. 15(2). doi:10.2136/vzj2015.05.0071

Hunt, A.G. 2016. Spatio-temporal scaling of vegetation growth and soil formation from percolation theory. Vadose Zone J. 15(2). doi:10.2136/vzj2015.01.0013

Liu, Y., G. Bisht, Z.M. Subin, W.J. Riley, and G.S.H. Pau. 2016. A hybrid reduced-order model of fine-resolution hydrologic simulations at a polygonal tundra site. Vadose Zone J. 15(2): doi:10.2136/vzj2015.05.0068

Nimmo, J.R. 2016. Quantitative framework for preferential flow initiation and partitioning. Vadose Zone J. 15(2). doi:10.2136/vzj2015.05.0079

Schulz, M., D. Stonestrom, C. Lawrence, T. Bullen, J. Fitzpatrick, E. Kyker-Snowman, J. Manning, and M. Mnich. 2016. Structured heterogeneity in a marine terrace chronosequence: Upland mottling. Vadose Zone J. 15(2). doi:10.2136/vzj2015.07.0102

Wilson, M.G., J.M. Mirás-Avalos, M. Lado, and A. Paz-González. 2016. Multifractal analysis of vertical profiles of soil penetration resistance at varying water contents. Vadose Zone J. 15(2). doi:10.2136/vzj2015.04.0063

Yakubova, G., A. Kavetskiy, S.A. Prior, and H.A. Torbert. 2016. Benchmarking the inelastic neutron scattering soil carbon method. Vadose Zone J. 15(2). doi:10.2136/vzj2015.04.0056