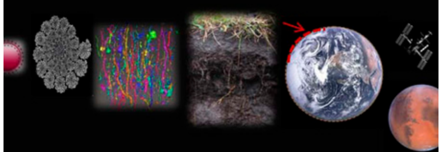
Special Section:
Soil Architecture and Function

L.W. de Jonge*
P. Moldrup
A.L. Vendelboe
M. Tuller
D. Wildenschild



The guest editors introduce the special section on Soil Architecture and Function. The contributions explore soil as Earth's life support system and how we must attain a deeper understanding by improving and linking measurement, visualization, and modeling of soil structure (architecture) and physical, chemical, and biological processes in different porous media systems and at different scales.

L.W. de Jonge and A.L. Vendelboe, Dep. of Agroecology, Faculty of Science and Technology, Aarhus Univ., Blichers Allé 20, P.O. Box 50, DK-8830 Tjele, Denmark; P. Moldrup, Dep. of Biotechnology, Chemistry and Environmental Engineering, Aalborg Univ., Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark; M. Tuller, Dep. of Soil, Water and Environmental Science, Univ. of Arizona, 1177 E. Fourth Street, Tucson, AZ 85721; and D. Wildenschild, School of Chemical, Biological, and Environmental Engineering, Oregon State Univ. Corvallis, OR 97331. *Corresponding author (lis.w.de.jonge@agrsci.dk).

Vadose Zone J.
doi:10.2136/vzj2011.0185
Received 28 Nov. 2011.

Soil Architecture and Physicochemical Functions: An Introduction

Soils function as Earth's life support system, a thin layer full of life covering most of the terrestrial surfaces. Soils form the foundation of society. Norman Borlaug stated in his Nobel laureate lecture that "the first essential component of social justice is adequate food for all mankind." If we are to provide this component while sustaining environmental quality in the midst of a growing population and rapidly diminishing resources, it is imperative to study and obtain a deeper level of understanding of soil functions using state-of-the-art technologies as well as provide the next generation of environmentalists, soil scientists, and environmental engineers with the best education possible. The 16 papers in this special section on soil architecture and physicochemical functions in the *Vadose Zone Journal* contribute to these goals by improving and linking measurement, visualization, and modeling of soil structure (architecture) and physical, chemical, and biological processes in different porous media systems and at different scales. Several studies in this special section also outline and discuss emerging and exciting interdisciplinary challenges for the rapidly growing vadose zone research community, including the need for enhanced public awareness of the soil's essential life-support functions, putting value on soil ecosystem services ("capital of soil"), and design of optimal soil-based growth media for long-term missions in space.

Understanding and improving soil functions is an enormous contemporary and future challenge for our profession because soils are generally recognized as the most complicated biomaterial on Earth, a final frontier for which the biophysicochemical constraints and controls are less explored and understood than the physical laws of planets and space (Curtis and Sloan, 2004; Young and Crawford, 2004). Present-day advances in the measurement of soil-water and soil-air transport and soil interfacial processes (e.g., water repellency and chemical sorption) in combination with revolutionary technological developments in porous media visualization (e.g., noninvasive imaging of soil by x-ray tomography) bring us a step closer to the final frontier of observing and understanding intact soil architecture and functions (de Jonge et al., 1999, 2009; Lazouskaya et al., 2006; Moldrup et al., 2007; Young and Crawford, 2004). Innovative merging of methods and models now supports the quantification of key soil functions including production, mobility, retention, and fluxes of "soil matter" (air, gases, water, solutes, colloids, chemicals, and biomass) in arterial pore networks. Close links among soil physics, chemistry, microbiology, hydrology, and pedology and related areas of the environmental, health, and space sciences should be explored and exploited for immense potential benefits for environmental sustainability and the protection of our precious environmental resources during the next decades.

Inspired by these challenges, the collection of papers in this special section of the *Vadose Zone Journal* originate from the First International **C**onference and **E**xploratory Workshop on **S**oil **AR**chitecture and Physico-Chemical Functions (CESAR), held at Aarhus University, Research Centre Foulum, Denmark, from 30 Nov. to 2 Dec. 2010 (de Jonge et al., 2010).

The conference was organized with a focus on interdisciplinary studies to foster and promote collaborations across disciplines and scales and to create a common road map for exploring soil inner space, its secrets, controls, and functions. Based on this goal, we defined the vision and mission of the CESAR conference.

The vision for CESAR activities was to lay the foundation for: (i) cutting-edge research on defining and understanding soil architecture and the sustainable functions of soils; (ii) promoting international, interdisciplinary collaboration in soil and environmental research; and (iii) educating the future generation of soil and environmental scientists.

The mission of CESAR was to stimulate collaborative research in the physics, chemistry, and biology of soils that, combined with emerging measurement, modeling, and visualization technologies, has the potential to significantly advance our understanding of all factors contributing to soil quality and its ability to sustain vital functions across a wide range of scales. Furthermore, the mission was to promote discussions on how we, as a scientific community, may convey strategic knowledge about the importance of sustainable soil functions in view of present and future food production, environmental, health, and climate issues to policymakers, politicians, and the public.

To fulfill this mission, the CESAR conference brought together established, world-leading scientists in environmental soil science research with some of today's most talented new researchers, as well as a large number of PhD and MSc students. With soil functional architecture as a mutual platform, the CESAR conference highlighted interdisciplinary challenges and pipeline research needs for the soil inner space—from biophysical processes at the nano- and microscales, via pedon- and catchment-scale water, colloid, and chemical transport, to optimal growth media for manned missions in outer space (Fig. 1).

More than 120 scientists and engineers from 17 countries participated in the CESAR conference. Among the many contributions, 16 papers are included in this special section of the *Vadose Zone Journal*, presenting exciting and emerging concepts and tools toward overcoming the final roadblocks to the exploration of soil inner space. The CESAR section contains four subsections, the first comprising two "soil future" concept papers, followed by three subsections each focusing on a central topical area of the conference (see Fig. 2).

The two first papers in the special section are focused on two of the emerging and most exciting challenges for our profession. Robinson et al. (2012) pose the question of how we can assign societal values to soil inner space functions and associated ecosystem services. This is needed to place soil and the vadose zone and their services to ecosystems, environment, and climate in a much more central position on the political agenda, including securing a place for sustainable soil services as part of future political decision tools.

As a transition from soil inner space to manned missions to outer space, if we want to migrate into space and create settlements, based on initial, long-term missions to Mars or distant exo-planets, we need to bring our soil and knowledge of the soil inner space processes with us as our life support system for providing food, cleansing water and air, and all other essential ecosystem services. Jones et al. (2012) discuss design criteria and review the newest scientific findings toward creating optimal growth media for reduced or microgravity conditions. Both Robinson et al. (2012) and Jones et al. (2012) identify and discuss a number of challenges ahead of us to succeed in "putting value on soil services" and "bringing soil services into space."

The first topical subsection comprises four papers focusing on major biophysical parameters and drivers for time-dependent soil architecture and vadose zone functions. Kristensen et al. (2012) introduce a new chamber method for measuring biodegradation rates of petroleum compounds on intact samples under natural

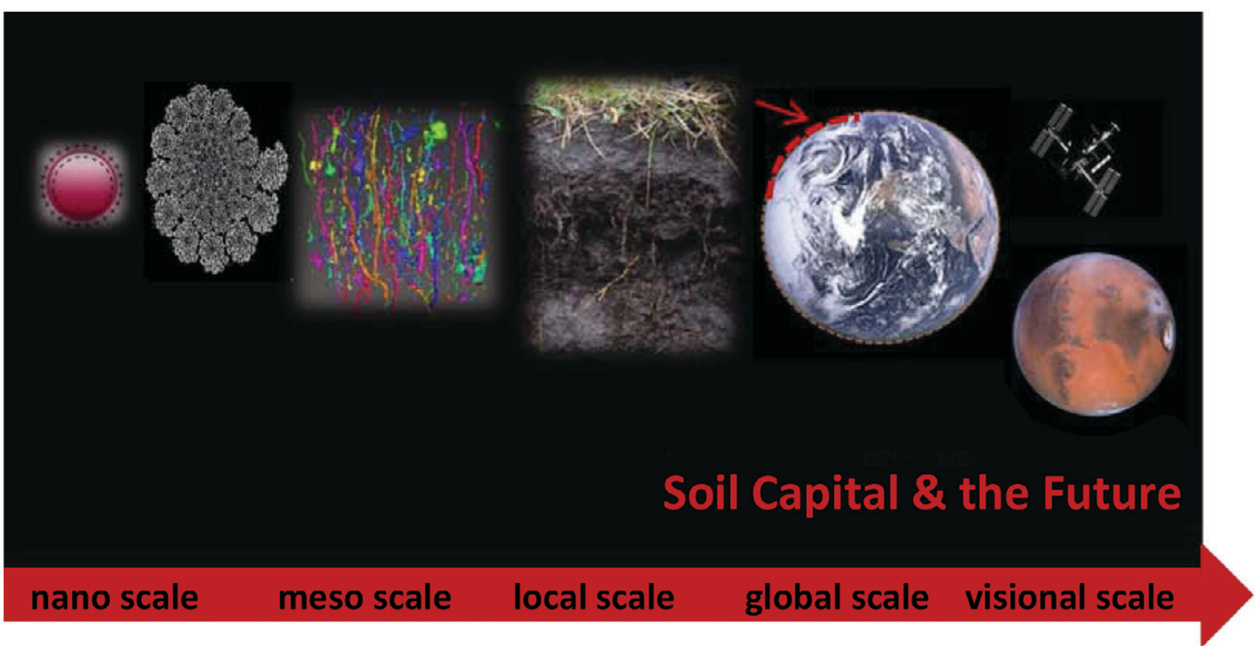


Fig. 1. Nanoscale to planetary knowledge of soil functional architecture.

diffusion-limited conditions. Initial results implied a limited effect of soil structure but a large influence of O_2 and petroleum vapor distribution and diffusion in the soil gaseous phase. Dissanayaka et al. (2012) present measurements of soil thermal properties (thermal conductivity and heat capacity) in different horizons of a peat soil. A new three-phase mixing model is presented and tested, implying that thermal properties for organic-dominated porous media are highly controlled by the liquid phase impedance factor and thus by the effective tortuosity and connectivity of the liquid-filled pore network and water films. Hamamoto et al. (2012) show that soil organic matter content is a main driver for soil gaseous-phase diffusion and tortuosity. Essential links among soil organic matter content, soil total porosity, and water blocking effects on soil-gas diffusivity and thus on air-filled pore network tortuosity are revealed, and a preliminary model capturing relevant diffusion processes is proposed. Subedi et al. (2012) investigated the dynamics of soil-water repellency in model soil systems, creating water-repellent particle surfaces by mixing with hydrophobic agents. They show that water repellency can be a highly time-dependent process, depending on the type of hydrophobic coating material, and suggest an exponential model for contact angle as a function of time. These four studies, seen as a whole, suggest that we need to simultaneously consider the air, water (including water repellency), and thermal parameters across moisture conditions to understand the basic building units of soil architecture, including pore and particle network connectivities and associated transport functions—a concept we may call the gaseous, liquid, and thermal infrastructure of soil inner space.

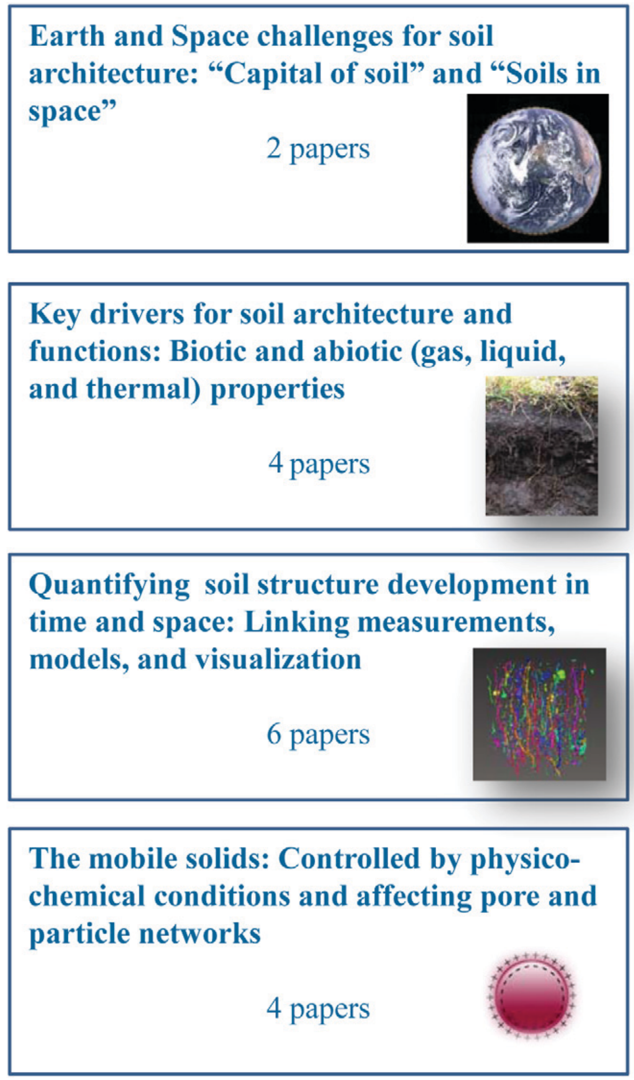


Fig. 2. Organization of the 16 papers in this *Vadose Zone Journal* special section on soil architecture and physicochemical functions.

The second subsection comprises six papers that focus on emerging methods and techniques for quantifying soil functions and visualizing changes in soil architecture and structure in time and space. Markgraf et al. (2012) quantified microstructural changes in soil architecture by applying a range of techniques including particle charge density, rheological tests, and visualization by scanning electron microscopy. They found that a carbonate- and clay-rich soil supported a highly stable soil structure with less soil crusting and surface sealing and discuss drivers for soil structural stability. Using model media ranging from glass beads to crushed tuff, Kulkarni et al. (2012) developed and tested an improved method for image segmentation of x-ray computed tomography (CT) data. They outline and discuss further potential improvements toward better representing and quantifying true three-dimensional soil architecture. Sammartino et al. (2012) present a novel method for visualizing preferential flow in intact soil cores using multislice helical CT. The method enabled them to follow the temporal development of preferential flow in intact cores by visualizing the amount of water in the macropores as a function of time and to identify and characterize the main, flow-active parts of the macropore networks. Badorreck et al. (2012) used micro-CT to reveal differences in soil surface pore structure and infiltration patterns caused by ground-dwelling beetle burrows. These so-called "ecological engineers" were found to be a major driver for initial soil development processes. Geoffroy et al. (2012) combined in situ gravity lysimeter measurements and HYDRUS-1D modeling to illustrate temporal changes in a virgin soil structure and its water flow regime following 3 yr of development in a constructed Technosol. Across soil type and conditions, both differentiating and generalizing soil functional behavior, Chamindu Deepagoda et al. (2012) suggest a soil architectural fingerprint derived from soil-gas diffusivity measurements from wet to dry conditions. They used the Buckingham (1904) tortuosity factor as a variable function of the soil-water matric potential and show that each soil exhibits a unique fingerprint and, also, that fairly simple equations for pore-network tortuosity can be developed at given matric potentials. In further perspective, the six papers together strongly illustrate that linking traditional and emerging soil physical and biophysical measurement methods and models with rapidly evolving soil visualization techniques comprises a powerful new development toward understanding and quantifying soil inner space and its essential functions.

The last subsection contains four papers devoted to the soil solids and especially the mobile colloids that, in part, control the ever-changing pore and particle networks and soil functions. Until two decades ago, soil particles and colloids were considered immobile across short time scales, but today we know colloids to be quite mobile, with the potential to facilitate colloidal chemical transport (de Jonge et al., 2004). Vendelboe et al. (2012) identified clay and, for some soils, the so-called "free clay" fraction (clay not complexed by soil organic carbon) as a main driver for water-dispersible colloids; they propose a simple, predictive model for colloid mobilization based on soils from different clay and organic matter gradients, also representing different climatic zones. Using a pore-scale model system, Qiu et al. (2012) studied colloid retention and attachment under different solution chemistry and flow conditions. Their measurements and modeling in combination with confocal-microscopy visualization revealed the hydrodynamic controls of colloid retention at pore walls. In experiments with model colloids, Shen et al. (2012) examined the effects of surface roughness on colloid detachment and show that a given fraction of colloids is released at low ionic strength, with results in good agreement with a newly developed conceptual model for colloid detachment. With a focus on clay dispersibility and soil friability, Schjønning et al. (2012) take a deeper look into the Dexter et al. (2008) clay/C saturation index and the concept of uncomplexed clay also applied by Vendelboe et al. (2012). They found that a clay/C ratio of $n = 10$ or a new, corresponding (clay + silt)/C ratio of 20 may serve as a practical threshold for clay dispersibility. In perspective, all papers point towards the need for more insight into controlling mechanisms for colloid mobility, including particle–wall interactions and mineral–organic matter interactions under different solution chemistry and flow conditions. This is especially important to understand and quantify the significance of the "mobile solids phase" for temporal development in soil architecture.

We envision that this special CESAR section will stimulate new research towards solving human and environmental challenges for a planet that has just rounded 7 billion people and has a great need to understand, value, and optimize soil ecosystem services.

Acknowledgments

The CESAR event was financed by the international project Soil Infrastructure, Interfaces, and Translocation Processes in Inner Space (Soil-it-is) granted by the Danish Research Council for Technology and Production Sciences (www.agrsci.dk/soil-it-is/), the International Network Programming initiative by the Danish Agency of Science Technology and Innovation, The Obel Family Foundation, the STAiR International Research Education Programme for Soil Technology and interdisciplinary Research in Soil and Environmental Sciences (http://stair.agrsci.dk), and the SAFE Graduate School of Agriculture, Food and Environment, Aarhus University.

References

Badorreck, A., H.H. Gerke, and R.F. Hüttl. 2012. Effects of ground-dwelling beetle burrows on infiltration patterns and pore structure of initial soil surfaces. Vadose Zone J. 11. doi:10.2136/vzj2011.0109

Buckingham, E. 1904. Contributions to our knowledge of the aeration of soils. Bur. Soil Bull. 25. U.S. Gov. Print. Office, Washington, DC.

Chamindu Deepagoda, T.K.K., C., P. Moldrup, P. Schjønning, K. Kawamoto, T. Komatsu, and L.W. de Jonge. 2012. Variable pore connectivity model linking gas diffusivity and air-phase tortuosity to soil matric potential. Vadose Zone J. 11. doi:10.2136/vzj2011.0096

Curtis, T.P., and W.T. Sloan. 2004. Prokaryotic diversity and its limits: Microbial community structure in nature and implications for microbial ecology. Curr. Opin. Microbiol. 7:221–226. doi:10.1016/j.mib.2004.04.010

de Jonge, L.W., O.H. Jacobsen, and P. Moldrup. 1999. Soil water repellency: Effects of water content, temperature, and particle size. Soil Sci. Soc. Am. J. 63:437–442. doi:10.2136/sssaj1999.03615995006300030003x

de Jonge, L.W., C. Kjaergaard, and P. Moldrup. 2004. Colloids and colloid-facilitated transport of contaminants in soils: An introduction. Vadose Zone J. 3:321–325.

de Jonge, L.W., P. Moldrup, and P. Schjønning. 2009. Soil infrastructure, interfaces & translocation processes in inner space ("Soil-it-is"): Towards a road map for the constraints and cross-roads of soil architecture and biophysical processes. Hydrol. Earth Syst. Sci. 13:1485–1502. doi:10.5194/hess-13-1485-2009

de Jonge, L.W., P. Moldrup, and A.L. Vendelboe (ed.). 2010. Proceedings of the first international conference and exploratory workshop on soil architecture and physico-chemical functions, Viborg, Denmark. 30 Nov.–2 Dec. 2010.

Dexter, A.R., G. Richard, D. Arrouays, E.A. Czyz, C. Jolivet, and O. Duval. 2008. Complexed organic matter controls soil physical properties. Geoderma 144:620–627. doi:10.1016/j.geoderma.2008.01.022

Dissanayaka, S.H., S. Hamamoto, K. Kawamoto, T. Komatsu, and P. Moldrup. 2012. Thermal properties of peaty soils: Effects of liquid-phase impedance factor and shrinkage. Vadose Zone J. 11. doi:10.2136/vzj2011.0092

Geoffroy, S., S. Ouvrard, B. Pey, J.L. Morel, and C. Schwartz. 2012. Predictability of soil structure evolution of a constructed Technosol using water flow modeling. Vadose Zone J. 11. doi: 10.2136/vzj2011.0069

Hamamoto, S., P. Moldrup, K. Kawamoto, and T. Komatsu. 2012. Organic matter fraction dependent model for predicting the gas diffusion coefficient in variably saturated soil. Vadose Zone J. 11. doi:10.2136/vzj2011.0065

Jones, S.B., D. Or, R. Heinse, and M. Tuller. 2012. Beyond Earth: Designing root zone environments for reduced gravity conditions. Vadose Zone J. 11. doi:10.2136/vzj2011.0081

Kristensen, A.H., C. Hosoi, K. Henriksen, P. Loll, and P. Moldrup. 2012. Vadose zone biodegradation of benzene vapors in repacked and undisturbed soil cores. Vadose Zone J. 11. doi:10.2136/vzj2011.0034

Kulkarni, R., M. Tuller, W. Fink, and D. Wildenschild. 2012. Three-dimensional multiphase segmentation of x-ray CT data of porous materials using a Bayesian Markov random field framework. Vadose Zone J. 11. doi:10.2136/vzj2011.0082

Lazouskaya, V., Y. Jin, and D. Or. 2006. Interfacial interactions and colloid retention under steady flows in a capillary channel. J. Colloid Interface Sci. 303:171–184. doi:10.1016/j.jcis.2006.07.071

Markgraf, W., F. Moreno, and R. Horn. 2012. Quantification of microstructural changes in Salorthidic Fluvaquents using rheological and particle charge techniques. Vadose Zone J. 11. doi:10.2136/vzj2011.0061

Moldrup, P., T. Olesen, H. Blendstrup, T. Komatsu, L.W. de Jonge, and D.E. Rolston. 2007. Predictive–descriptive models for gas and solute diffusion coefficients in variably saturated porous media coupled to pore-size distribution: IV. Solute diffusivity and the liquid phase impedance factor. Soil Sci. 172:741–750. doi:10.1097/SS.0b013e3180d0a423

Qiu, C.Q., J. Han, H. Gao, L.-P. Wang, and Y. Jin. 2012. Pore-scale numerical and experimental investigation of colloid retention at the secondary energy minimum. Vadose Zone J. 11. doi:10.2136/vzj2011.0071

Robinson, D.A., N. Hockley, E. Dominati, I. Lebron, K.M. Scow, B. Reynolds, et al. 2012. Natural capital, ecosystem services, and soil change: Why soil science must embrace an ecosystems approach. Vadose Zone J. 11. doi:10.2136/vzj2011.0051

Sammartino, S., E. Michel, and Y. Capowiez. 2012. A novel method to visualize and characterize preferential flow in undisturbed soil cores by using multislice helical CT. Vadose Zone J. 11. doi:10.2136/vzj2011.0100

Schjønning, P., L.W. de Jonge, L.J. Munkholm, P. Moldrup, B.T. Christensen, and J.E. Olesen. 2012. Clay dispersibility and soil friability: Testing the soil clay-to-carbon saturation concept. Vadose Zone J. 11. doi:10.2136/vzj2011.0067

Shen, C., L.-P. Wang, B. Li, Y. Huang, and Y. Jin. 2012. Role of surface roughness in chemical detachment of colloids deposited at primary energy minima. Vadose Zone J. 11. doi:10.2136/vzj2011.0057

Subedi, S., K. Kawamoto, L. Jayarathna, M. Vithanage, P. Moldrup, L.W. de Jonge, and T. Komatsu. 2012. Characterizing time-dependent contact angles for sands hydrophobized with oleic and stearic acids. Vadose Zone J. 11. doi:10.2136/vzj2011.0055

Vendelboe, A.L., P. Moldrup, P. Schjønning, D.J. Oyedele, Y. Jin, K.M. Scow, and L.W. de Jonge. 2012. Colloid release from soil aggregates: Application of laser diffraction. Vadose Zone J. 11. doi:10.2136/vzj2011.0070

Young, I.M., and J.W. Crawford. 2004. Interactions and self-organization in the soil–microbe complex. Science 304:1634–1637. doi:10.1126/science.1097394