Special Section: Scaling in Soil and Complex Porous Media

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Scaling in Soil and Other Complex Porous Media

Scaling is becoming an increasingly important topic in the earth and environmental sciences as researchers attempt to understand complex natural systems through the lens of an ever-increasing set of methods and scales. The guest editors introduce the papers in this issue's special section and present an overview of some of the work being done.

Scaling remains one of the most challenging topics in earth and environmental sciences, forming a basis for our understanding of process development across the multiple scales that make up the subsurface environment. Tremendous progress has been made in discovery, explanation, and applications of scaling. And yet much more needs to be done and is being done as part of the modern quest to quantify, analyze, and manage the complexity of natural systems. Understanding and succinct representation of scaling properties can unveil underlying relationships between system structure and response functions, improve parameterization of natural variability and heterogeneity, and help us address societal needs by effectively merging knowledge acquired at different scales.

For 20 years, the problem of scaling in soils and related heterogeneous media has been addressed at international PEDOFRACT workshops organized by the Fractal Applications Group from Universidad Politécnica de Madrid, Spain. Previous meetings organized by this group resulted in special issues of the journals *Ecological Modelling* (Martín et al., 2005), *Geoderma* (Pachepsky et al., 2006), *Vadose Zone Journal* (Perfect et al., 2009), and *Ecological Complexity* (Martín et al., 2009). PEDOFRACT 2012 was held on 3–6 July 2012 in La Coruña, Spain and attracted approximately 35 participants from 11 different countries. Selected papers from that meeting were submitted to the *Vadose Zone Journal* and subjected to the journal's rigorous peer review process. This special issue contains original contributions covering a wide range of views and approaches to scaling in natural and constructed porous media.

Scaling laws in the subsurface environment rarely hold for (space of time) lags spanning more than two orders of magnitude and typically fail at small and large separation distances. Soils present various examples of such breaks in scaling and parameterization. The works of Ibáñez and Feoli (2013) and Caniego Monreal et al. (2013) demonstrate the way scaling is manifested in soils in the ultimate coarse range of scales by focusing on regional and global scale studies of soil cover. Caniego Monreal et al. (2013) investigated the fractal structure of the complex geographical patterns of major pedotaxa classified in Europe. The authors employed lacunarity to quantify the degree of regularity associated with the local and global abundance of different soil types. Well-defined power laws appear to be applicable to describe pedodiversity, that is, the occurrence of a variety of soil taxonomic units. A key result is the demonstration of the ability of the methodology to provide sharp classifications of pedotaxa and relate this classification to dominant patterns of different soil types. Lacunarity appears to be a useful parameter, complementary to power law scaling exponents, for quantification of textural properties of large-scale spatial patterns. In this context, management and organization of regional and global inventory projects can benefit from considering fractal scaling evidences to monitor the evolving dynamics of earth cover, as affected by anthropogenic and natural actions. The results exposed in these works pose an intriguing epistemological question of whether apparent scaling arises due to the human perception on which classifications might be based. If so, do humans classify the world with scaling in mind?

Within investigation windows of relatively limited extent, such as watershed scales, improved quantitative information about soil forming factors (i.e., climate, biota, parent material, and topographic features) become available. While there is a feedback between key physical processes and scale variability characteristics of such factors (e.g., relationships between climate and topography, peat material and topography, climate and biota), the way scaling of these factors manifests itself and can be described remains an intriguing question. The work of Cámara et al. (2013) addresses this topic by focusing on

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an example given by the relationship between spatial scaling of the type of parent material and the first-order drainage network. The results of the study reveal a close relationship between the evidenced power law scaling parameters and system lacunarity. This way of approaching the description of the system can benefit the development of techniques for (i) spatial predictions using existing information and (ii) construction of synthetic datasets to evaluate reliability of measurement and modeling techniques. Another scale-related issue for this range of scales is the derivation of effective parameters for flow, fate and transport models. One recurrent research topic is investigating whether and how averaging of the results of smaller-scale simulations can serve as a productive approach. For sink-source terms, this topic is represented in this special issue by the work of Andreasen et al (2013), who used the one-dimensional modeling to interpret soil moisture data associated with a heterogeneous catchment scale setting. Effective parameters derived by means of averaging techniques or inverse estimation proved to contain relevant information to describe the mean system behavior at the catchment scale in terms of evapotranspiration and groundwater recharge.

At typical field-scale observation windows, spatial variability of soil, sediment, and rock properties is the topic of primary interest in burgeoning areas of model performance assessments, multimodel analysis, uncertainty quantification, data assimilation, and coupled upscaling and downscaling. In essence, all these activities rely on the quantification of the uncertainties associated with modeling results in the presence of scarce and uncertain measurements (eventually) distributed on a multiplicity of scales. Matching the scale of application and the scale of measurement variability becomes imperative, and scaling is the procedure to approach this. In this context, there is a considerable interest in developing new field- (or laboratory-)scale models of space (or spatiotemporal) scaling and analyzing in a comparative framework the results stemming from different modeling approaches. These studies explore the spacing aspect of scaling, and future advances are expected where both spacing and support variations are included in scaling models. Towards this end, Vidal-Vázquez et al. (2013) employed fixed size multifractal analysis to document the scaling patterns and structural heterogeneity of tropical soil attributes measured along two perpendicular transects. Spatial distribution of the soil attributes analyzed (i.e., texture, pH, organic carbon content, exchangeable Ca^{2+}, H^{+} and Al^{3+}, exchangeable bases, cation exchange capacity, and percent base saturation) display different degrees of scaling heterogeneity or multifractality. Scaling is characterized though the generalized dimension, mass exponent function, and singularity spectra functions. The latter are found to be associated with a mild to strong degree of asymmetry, depending on the type of attribute. The work of Rodríguez-Gómez et al. (2013) explores the temporal variability of climate variables that present a strong local behavior. They developed three models of solar radiations (global, diffuse, and direct) using the autoregressive integrated moving average (ARIMA) methodology for data collected in A Coruña by the Spanish Agency for Meteorology. Performances of these models are then tested using the multifractal detrended fluctuation analysis (MFDFA). The authors found that the model of global irradiation reproduces the main statistical characteristics of the data series (i.e., scale exponent values and points of slope change) and, in general, the multifractal behavior of the system. The diffuse model displays a behavior similar to that of the analyzed data series for short-term large fluctuations, whereas the model for direct irradiation was not capable to interpret the multifractality of the data. The recent interest to spatiotemporal variability in soil water content and other soil variables (Vanderlinden et al., 2012) poses a challenge of combining scaling of climate, soil, and topography controls to interpret such variability at the observation scale.

Scales of horizon, facies, or individual blocks or samples of porous media that are manageable in a laboratory context have been the most common sources of data to document and explain scaling behaviors. In particular, one of the early promises of fractal geometry applications in soil science was the use of changes in scaling parameters describing pore space geometry to diagnose early structural changes caused by environmental conditions and/or management practices. However, controls other than structural change may affect scaling of soil parameters. The work of Riva et al. (2013) explores scaling of key statistics of minipermeameter data of air permeability of a centimeter-scale block of Berea sandstone. These authors provide direct evidence that data and their increments are consistent with sub-Gaussian random fields subordinated to truncated fractional Gaussian noise—their statistics and scaling behavior being dependent on direction. The scaling behavior of the data and their increments is seen to be consistent with that displayed by sub-Gaussian random fields subordinated to truncated fractional Brownian motion through a Lévy stable subordinator. The data exhibit extended self similarity (ESS). The authors suggest that these behaviors can be considered as general and applicable to diverse data collected over a multiplicity of scales. The work of Lado et al. (2013) shows that chemical composition of soil can be the strongest factor affecting scaling properties of the process of nitrogen adsorption on organoclays. Similarly, a good correlation of the nitrogen adsorption scaling parameters with soil properties was observed in the work of Paz-Ferreiro et al. (2013a) on tropical soils. Multifractal parameters of nitrogen adsorption scaling provided more information than specific surface area estimates and were best correlated with organic carbon and clay content. This, however, was not the case in the work of Sanjurjo Sánchez and Vidal Vázquez (2013) where the effect of chemical composition of granitic rocks is seen not to affect scaling properties of the mercury intrusion isotherms, the time of exposure to weathering appearing to be the only reliably correlated variable. Both water content and bulk density affected parameters of the multifractal scaling of soil penetration resistance in the work of Paz-Ferreiro et al. (2013b). Standardization of chemical composition and dynamic soil variables appears to be needed to provide an effective depiction of structural changes in soils and other porous media using scaling arguments.

Fragmentation is a traditional staple of scaling studies in porous media. It continues to be of interest, particularly because particle size distributions play a notable role in estimating various physical and chemical porous media properties related to the ability to store and transmit water, chemicals, heat, and electrical charge. The information about particle size distribution is often associated with a limited number of particle size classes, and there are indications that an improved level of detail would be beneficial in media property estimations. The work of Martín et al. (2013) demonstrates how a scaling model can allow one to generate detailed particle size distribution from incomplete information. Key points addressed in the manuscript include (i) the attempt to develop a unified mathematical formulation that embeds empirical observations of physical properties of granular media in the (statistical) characterization of particle size distributions and provides a rigorous theoretical description underpinning the observed power law behavior of grain size distributions and (ii) an appraisal of the way these formulations could be employed in practical applications to simulate particle size distributions of granular media. In answer to these points, a theoretical generative model is presented to enable reproducing observed self-similar behaviors of particle size distributions of soil aggregates. The common particle size distributions are based on the sample fragmentation, and it remains to be seen how a fragmentation procedure can be factored within scaling models.

Scaling related to transport parameters in porous media is acknowledged, but more information is needed to understand its origin and manifestation. The experimental investigations of Kang et al. (2013) focused on measurements of sorptivity and unsaturated diffusivity of Berea sandstones using neutron radiography provide a data set documenting the complex structure of these parameters. The work represents the first application of neutron imaging to investigate transient capillary flow in Berea sandstone and provides the first published estimates of unsaturated diffusivity and sorptivity for this medium. Although these parameters are well established in soil physics, geology, and petroleum engineering, their availability is limited in the context of Berea sandstone, which is the reference material in these fields. As such, the data set provided is timely, critical, and highly valuable because it has the potential of forming the basis for subsequent advanced studies describing the way transient fluid movement develops under scale dependent variably saturated conditions.

Scaling appears to be needed in fate and transport modeling applications where sizes of grid cells are often much larger than the sizes of samples on which soil hydraulic and transport properties are measured at the laboratory scale. The work of Cheng et al. (2013) explains how the rigorous upscaling of water retention parameters can be performed in such a case. Additional work in this direction on flow and transport parameters is of substantial interest for applications. One research direction to pursue here is to combine estimates of flow and transport parameters from readily available data at the laboratory scale with techniques that allow upscaling to the grid scale, thus exploiting the rich information content embedded in pedotransfer functions and geotechnical correlations.

Scales finer than that associated with geological or soil horizons have become a notable source of data in critical zone media with the advent of modern computer tomography. Scaling plays a key role in processing and extracting information from these types of data that are difficult to handle with traditional data analysis methods. Changing scale with imagery usually includes complementary algorithms of image coarsening. Research is underway to explore the effect of such algorithms on apparent scaling manifestations. A type of such algorithms, which is based on Minkowski functionals, was successfully applied in the work of San José Martínez et al. (2013) to X-ray tomographic images of soil columns to demonstrate the effect of soil management on scaling in pore structure parameters. The coupling of coarsening and image segmentation algorithms is promising to provide improved insights into structural differences and evolution of soils studied with the aid of computer tomography imagery.

This special issue illustrates the remarkable role and place of scaling in earth sciences. Earth (geophysical and environmental) variables and processes display scaling across a multiplicity of observation domains. This impacts our ability to provide predictions of key processes on the basis of limited observations collected on different (measurement) scales (volumes) within observation domains (windows) of variable sizes. It also affects model structure/development and therefore our ability to discriminate between different models. Most of the work in this volume shows that fractal and multifractal theories allow synthetic characterization of scaling of key statistics through a limited set of parameters that is typically compatible with the paucity of available information.

The current grand challenge is posed by the need to have at our disposal a unified theory that includes all (multi)fractal manifestations. Different methodologies proposed in the literature bring to light various aspects. Each of these provides an incomplete picture and highlights only features that are relevant to the particular process and observation domain/window under investigation. Efforts toward the formulation of a unified theory are still in progress. An example is offered by the interpretive scheme on which the work by Riva et al. (2013) relies and which reconciles within a unique theoretical framework a wide range of scaling manifestations observed in nature. These include linear or nonlinear power law scaling in a midrange of space and/or time lags, breakdown in power law scaling at small and large lags, recovery of power law scaling at such lags via extended self similarity, lack of apparent consistency between sample frequency distributions of data and their increments, and, in some cases, decay of increment sample frequency tails with increased lag. All these should be rigorously framed and clearly and convincingly demonstrated on the basis of experimental/empirical evidences at multiple scales. The results of such analyses could then be cast into physically based stochastic models depicting process dynamics.

Scaling is an important component of the pathway from the data we have to the data we need. Societally important decisions have to be made at coarser scales, and yet the feasible data collection occurs at finer scales. Mechanisms responsible for the efficiency of management practices are revealed at finer scales and yet the efficiency of those practices is evaluated at coarser scales. Scaling appears to be increasingly relevant as the observations at both fine (e.g., tomography) and coarse (e.g., remote sensing) generate "big" data—datasets so large and complex that it becomes difficult to process using on-hand database management tools or traditional data processing applications. Efficient scaling tools hold a promise to condense large datasets into usable information. Overall, the efficient transfer of information between scales becomes a must.

Readers of this special issue will be delving into representative examples of the status and evolution of data-driven research into scaling in complex natural systems. The invaluable help of the anonymous reviewers is acknowledged and highly appreciated. The guest editors sincerely hope that this diverse collection of papers demonstrates the value of scaling research for improved understanding Earth's environment.

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