Editorial for the Special Issue on 'Advances in soil scaling: theories, techniques and applications'

Scale is an essential concept in the description of soils. The bulk of empirical information on soils is obtained at fine scales, whereas assessment of environmental trends and scenarios requires information and decisions at much larger scales. The quest to discover how soil information can be linked across scales is an important focal point of soil science.

Relating soil properties and processes at different scales has been the focus of the series of PEDOFRACT conferences organized by the Group of fractal studies at the Technical School of Agronomic, Food and Biosystem Engineering at the Universidad Politécnica de Madrid (UPM). The PEDOFRACT IX conference took place in Barco de Avila, Spain in July 2019. Scientists from 15 countries participated. The conference theme was "Advances in soil scaling: theories, techniques, and applications". This special issue of the EJSS presents selected contributions to the meeting programme and related work. The conference encompassed research at various hierarchical scales, including pore, aggregate, horizon, pedon, and coarser scales. Within these hierarchical scales, researchers varied the measurement scale, i.e. sizes of the support, the distance between measurement locations, and the total extent of the measurement domain. Some works addressed the classical question if there exist dependencies of soil properties on scales that are valid within a range of scales, and if they exist, whether coefficients in those dependencies can be related to soil genesis and management. Other authors were more interested in observing and interpreting differences in soil process manifestation, appearing as scale changes.

Research at the pore and aggregate scale mostly addressed the characterization of soil structure. The classical approach relies on 2D soil imaging and the use of the multifractal model. The latter model assumes that the statistical moments of the measurement follow the power-law dependence on the measurement scale. A comprehensive summary of the multifractal modeling is presented by Perrier et al. (this issue), who applied it to the two-dimensional image of a soil

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thin section. The authors concluded that this model is applicable in a range of scales but creates artifacts if applied outside of this range.

The onset of the X-ray computer tomography (X-ray CT) provided new opportunities of quantifying scale dependencies of soil properties in three dimensions. Gerke et al. (this issue) observed substantial differences in scaling when the scale is defined in terms of the support size or the spacing size. These authors imaged samples from Ah and B horizons of the Haplic Greyzems. They computed porosities and simulated flow in the complex pore space for a set of progressively increasing subsamples of their original samples. They observed the emergence of the representative elementary volume. The increase of the subsample size beyond REV did not lead to the significant change in saturated hydraulic conductivity of porosity. The authors also defined correlation functions that showed the features of the pore space as functions of spacing. As they changed the subsample size, they discovered that correlation functions depended on scale and continued to change beyond the representative elementary volume scale threshold.

Somewhat similar differences in scale-dependence of structural metrics were observed by Lucas et al. (this issue). They used data from X-ray CT imaging of samples of three distinctly different sizes to observe the scaling behavior of two pore connectivity metrics: the Euler number and gamma indicator. The former reflects the degree of pore connectivity irrespective how far the connections are, while the latter was sensitive to long-range connectivity. The increase in the sample size did not affect the Euler number but critically modified the long-range connectivity because the larger samples had long pores created by root systems and tillage.

Segmentation of images, i.e., separation of pore space from solids, has been and remains a necessary preprocessing operation before any study of scale dependencies at pore or aggregate scale. This operation with X-ray CT imagery can lead to additional uncertainty, especially if parts of the pore space is filled with loose organic material (Gerke et al., this issue), or include incompletely saturated pores (Guber et al., this issue). The latter authors proposed an elegant solution of the segmentation problem based on saturating the soil sample with a salt solution that exhibits an abrupt and notable change of the mass attenuation coefficient at the threshold level of the beam energy. Then, the masses of this salt solution in the pores and the pore volumes could be estimated by subtraction of images made with the beam energies just above and just below this threshold level.

As scale changes, the intensity of some processes changes, or new processes begin to operate. Working with samples from the A horizon of the well-drained Alfisol, Kravchenko et al. (this issue) demonstrated that microorganisms localized in large pores respond to new carbon inputs with faster turnover, greater growth, and more intensive enzyme production compared to those inhabiting the small pores. The large pores are not adequately observable at fine scales and, therefore, only low-intensity carbon consumption and transformation can be detected. Similarly, fine-scale studies could not be used to characterize bio-pores generated by root systems in the work of Lucas et al. (this issue).. In contrast, the transition to coarser scales provided data on the connectivity in soils due to the presence of such pores.

The ability to model and simulate soil pore spaces creates an efficient means to study the effect of pore structure on flow and transport in soils as well as chemical and biological processes at different scales. Perrier et al. (this issue) demonstrated the opportunities of simulating soil pore spaces using the multifractal model. An exhaustive set of parameters for soil structure quantification is not established, and may not exist. However, feature extraction from large volumes of data from X-ray CT imagery is highly desirable. Karsanina et al. (this issue) imaged samples from the A horizon of arable and forested Chernozems and used the spacing dependencies of four types of correlation functions for a comprehensive description of soil structure. They found that 72 parameters can provide an accurate quantification of the correlation functions so that the complex three-dimensional directional properties of soil structure can be reduced to a limited set of parameters. For any structure parameterization, it needs to be determined how it can be used for building a synthetic random soil structure, and what performance criteria can be applied to evaluate these constructed samples.

At the pedon scale, modelling the scale-dependence of the spatial variability of soil properties is a traditional topic of scaling studies. For several soil properties, multifractal modelling has been efficient in the description of the variability dependence on spacing along transects. A less researched topic is the spatial relations between the variability of correlated properties. Farias de França e Silva et al. (this issue) analyzed data on plant micronutrients measured with two different methods along a soil transect. The multifractal model was applicable for data obtained by each of the methods. The joint multifractal analysis showed that the relationship between scaling parameters (obtained across multiple scales) was stronger than the relationship between measurements with two methods obtained at the same scale.

Sensor-based high-frequency monitoring of soil variables provides time series that may exhibit scaling properties. Time series of soil water contents at three depths were researched in the work of San Jose Martinez et al. (this issue) under two types of cover crops in the vineyard interrow. The authors demonstrated that the multifractal model was applicable to the detrended time series, and that the analysis of shuffled time indicated the presence of memory in the form of long-range correlations. This complex structure changed with depth.

At very coarse scales, soil cover is a major control of ecosystem dynamics and scaling. Urgilez-Clavijo et al. (this issue) observed scaling in spatial patterns of deforestation in two Ecuador Biosphere Reserves and investigated how this scaling reflected properties of soils. The authors found that multifractal scaling patterns were spatially dependent on the initial deforested patchiness state, the distance to the adjacent deforestation patches and soil suitability for agricultural activities and potential soil degradation, being interconnected drivers of deforestation dynamics and scaling. As the pedodiversity manifests itself in scaling of soil spatial units, it affects scaling of ecological land units for which the spatial pattern of soil is an important control. Ibanez et al. (this issue, 2020a.b) analyzed scaling patterns in maps of land systems that were defined as areas or group of areas throughout which there is a recurring pattern of topography, soils, and vegetation. The example of mapping land systems in the Alentejo-Centro-Extremadura Euroregion demonstrated scaling that emerged from superposition of several map layers. The authors emphasize the need to conceptualize map-based ‘number-scale’ relationships in terms of Pareto rather than Gaussian distributions (Ibanez et al., this issue, 2020a,b).

The transition of information from one hierarchical soil scale to another presents the daunting yet very important task in the application of scaling. To address practical societally important issues, measurements made at fine scales have to be converted to soil parameters of coarser scales (Bierkens et al., 2000). The same soil functions are characterized by different parameters at different hierarchical scales (e.g. water retention curve and water holding capacity). Conversion from one set of parameters to another cannot be achieved by a mechanical increase of the measurement scale (Vogel, 2019).

One direction of research to relate soil parameterization at different hierarchical scales employs the concept of pattern (Vereecken et al., 2016). One research direction refers to predictability of patterns at coarse scales. Patterns are defined as recurrent features in systems' behavior or appearance that can be observed in space, over time, or across scales. Knowing patterns is of utmost importance because they allow for or help predictions of the system behavior, elucidate the system development, help to diagnose changes, to set efficient monitoring, and to improve management practices. Processes operating at finer scales reveal themselves as a pattern at coarser scales. Therefore, the transfer of information between scales may amount to relating processes and patterns. One example of such relation is given by Vanderlinden et al. (this issue) who observed patterns of field water states under long-term direct drill and conventional tillage and related them to water retention parameterization at the finer (ped/aggregate) scale. In their research on a Haplic Vertisol soil under wheat-sunflower-pea rotation, the authors demonstrated that the preferred field water states and the recurrent differences between soil water regimes at the direct drill and conventional tillage sites could be explained by water retention features at the ped/aggregate scale.

This introductory note cannot go in detail of the conference discussions of challenges and opportunities for the scale research in soils. It was observed that the emphasis on rare occurrences which is intrinsic for scaling studies appears to be very important. Such occurrences at one scale of hierarchical soil organizations control soil functioning at the next higher scale (e.g. macropores at the ped level and infiltration at the pedon scale, carbon processing at the pore scale and soil respiration at the ped or pedon scale, elevated areas in the gilgay relief, and areal salinity, troughs delineating polygons in tundra soil cover and areal soil water balance, etc.). For that reason, understanding and quantifying scaling appears to be useful in addressing extreme events such as floods and landslides at the pedon scale, and land surface interactions at the soil series scale and coarser scales that are essential for regional atmospheric modeling and interpretation of remotely-sensed data. Progress needs to be made in understanding mechanisms and processes causing scaling in soils. It remains to be seen if existing definitions of scale via hierarchies, measurement metrics, and similitude (Pachepsky and Hill, 2017) are sufficient for scaling research. Also, measurement scale-based scaling may need model development beyond the multifractal model. Given current knowledge of scaling in soils, we can re-evaluate thresholds and boundaries in some soil classifications, e.g., textural classes. Novel sensing and imaging technics bring very large volumes of data. Scaling appears to be an efficient way of data compression. Currently, these data are so voluminous that they allow the application of sophisticated machine learning and AI techniques. It may be possible to steer and improve the feature extraction in these methods, knowing or expecting scaling properties. Overall, scaling in soils offers exciting research avenues to follow.

This special issue presents to the readers a taste of the current international effort to understand and quantify scale dependencies in soils. The anonymous reviewers have provided invaluable help, which is highly appreciated. The guest editors believe that the diverse collection of papers illustrates progress and importance in understanding multiscale soil systems and their functioning in the Earth biosphere.

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