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Editorial

Scaling, fractals and diversity in soils and ecohydrology

1. Introduction

The International workshop "PEDOFRACT 2002" was held on 27–30 June 2002 in El Barco de Avila, Spain. The workshop attracted a group of scientists from 10 countries concerned with the pervasive problem of analyzing environmental processes and properties over different spatial and temporal scales. This special issue reports on the results of that meeting. We would like to express our gratitude to all of the contributors to this special issue, and to the reviewers who were willing to put their time and effort into detailed and constructive reviews. We are also grateful to professor S.E. Jørgensen for his willingness to help in publishing this special issue. The financial support is obtained from Universidad Politécnica de Madrid, E.T.S.I Agrónomos and Dpto. de Matemática Aplicada a la Ingeniería Agronómica (Madrid, Spain) is kindly acknowledged.

2. Soils and ecohydrology

The workshop was organized around the theme "fractal approaches in scaling soil and hydrologic processes and properties." Soil measurements are either explicitly included in an ecological model or are considered implicitly as a backdrop for functioning of the biological system in question. In both cases, the representation scales of the environment and biological system have to be related. Soil properties are needed to understand and manage natural systems spanning an extremely wide range of scales. Methodologies for soil measurements are often vastly different at different scales. This creates a fundamental problem for both soil scientists and users of soil data. Many soil data sets are obtained from small samples and cores, monoliths, or small field plots, yet the goal is to reconstruct soil properties across fields, watersheds, and landforms, or to predict physical properties of pore surfaces and the structure of pore space as microbial habitats in the plant root zone environment. Hydrologists face similar issues. As the proportion of studies focusing on terrestrial systems continues to increase (Jørgensen, 2000), the proper portrayal of soil and hydrological processes at different scales is of the utmost importance.

3. Scaling, fractals and diversity

Scale is a complex concept having multiple connotations reflected in the majority of papers in this special issue. A notion of *support* is important to characterize and relate different scales in soil. Support is the length, area, or volume for which a single value of a soil property is defined; no variations in this or other properties are taken into account. Volume of an individual soil sample and size of the discrete spatial element in a soil model are typical examples of supports. The term "resolution" is often used for supports defined in terms of length, and the term "representative elementary volume" is applied for supports defined as volumes. The terms "pixel size," "grid size," or "grain" are also used to define support. An area or a volume that is sampled with given support determines the *extent* of measurements. Yet another notion, *spacing*, i.e. distance between sampling locations, is of importance in characterization of the scale of an experiment or application. Any research on soil properties or hydrological processes is conducted with specific support, extent and spacing. If those

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properties are to be used with a different support, extent or spacing, a *scaling* becomes necessary. Scaling is used as a noun to denote a relationship between soil or hydrologic data at different scales or as a verb to denote an action of relating such data at different scales. Upscaling (downscaling) usually refers to soil and hydrologic properties at a support that is larger (smaller) than the one at which data are available.

Definition of scale in geometrical terms facilitates the use of advances in geometry to relate data and processes at different scales. Fractals have been found to provide an appropriate mathematical tool to address the issues of structure and scale in environmental sciences. Fractal geometry was developed to describe the hierarchy of ever-finer detail in the real world. Natural objects often have similar features at different scales. Measures of these features, e.g. number, length, mass, roughness, surface area, abundance, etc. are dependent on the scale at which the features are observed. Fractal models assume that this dependence is the same across the range of scale, i.e. scale invariant within this range. Such models contain parameters that relate features at one scale to those at all others, and as such they present an appealing methodology for linking processes across scales. Applications of fractal geometry in soil and hydrological studies have grown exponentially (Pachepsky et al., 2000). They provide a framework within which multidisciplinary studies can be conducted and the complex relations between different soil and hydrologic processes can be understood.

Although biodiversity has become a major topic in ecological research, few studies address soil diversity, or pedodiversity. Soils are closely related to flora and fauna, and biodiversity characterization remains incomplete without pedodiversity portrayal. Soil taxonomy provides means to isolate distinct spatial units where soil cover has a specific range of properties that can be juxtaposed with other ecosystem features. As more knowledge is being accumulated on soil diversity, it can serve to illuminate and complement the data on scaling and diversity in ecosystems. Both diversity indices and relative abundance of soil taxa can be investigated, with the rich methodology developed already for flora and fauna. Availability of digital soil maps at various scales has created a readily available data source that can stimulate progress in quantifying and understanding pedodiversity.

4. Studies in the special issue

The studies in this special issue are briefly described below to delineate areas of emphasis and impact.

4.1. Methodological considerations

The use of fractal models is far from being straightforward; there exist many subtleties in the application and interpretation of available techniques. The studies in this section focus on new methodologies for quantifying scaling in ecohydrologic systems.

Martin et al. have proposed a balanced entropy index that modifies traditional Shannon entropy values by taking into account differences in class sizes. The index serves as a diversity measure, and is applied to soil textural data, as well as to body size variations of living organisms. Standard textural data can be viewed in a more general sense as an example of mass size distributions typical in the Earth and Life sciences.

The geometric nature of fractal models does not preclude their use for time series analysis. Multiscale characterization of time series is addressed in the paper by *Bandt*. Robust methods of time series analysis are introduced and applied these methods employ comparisons of values and contain a scale parameter that allows temporal data sets to be studied at different scales.

4.2. Pedodiversity and spatial variability

Ibáñez, et al. show that scale-dependence in soil cover properties can be assessed using concepts of diversity. In the first paper by this group digital soil maps are used to demonstrate that ecological notions of nestedness and taxa-range size distributions are fully applicable to soil entities such as pedotaxa and pedological assemblages. The scale-dependencies are surprisingly similar to those reported in the ecological literature (i.e. Jørgensen et al., 1998). Pedodiversity analysis also has practical implications for designing reserves for biological and pedological conservation. Other aspects of pedodiversity are explored in a second paper from this group. For the example of the Aegean islands, pedotaxa-abundance distributions are shown conform to abundance distribution models proposed in ecology, while pedorichness-area data fit diversity-area models.

Quantification of soil spatial variability in terms of soil map purity across multiple scales is important in ecological modeling, environmental prediction, precision agriculture, and natural resources management. *Lin et al.* investigate the variability of soil map units and soil properties at multiple scales using two case studies, and demonstrate that soil spatial variability is a function of map scale, spatial location, and the soil property in question. The scale hierarchy in soil spatial variability appears to be important for determining at what scale the variability is most likely to occur.

Yet one more approach to reveal scale dependencies in soil cover is using variable spacing to infer the applicability of multifractal variability models from typical geostatistical data. *Caniego et al.* compare two methods to evaluate multifractality with data on organic matter content, soil pH, and depth of Bt horizon measured along transects. Both methods indicate the applicability of the multifractal model of multiplicative scaling to soil variability.

4.3. Soil physical properties

Soil texture defined in terms of particle size distribution is a leading indicator of soil properties and functioning. Novel experimental techniques provide new insights into the properties of these distributions. The paper by *Montero* demonstrates that multifractal scaling models are germane to soil textural composition data collected using laser diffractometry applied to a range of soils with widely varying properties.

Soil structure is an important factor in the functioning of terrestrial ecosystems. Relationships between the density of soil aggregates and their size provide a way to use aggregate-related information in soil structure characterization. *Guber et al.* have investigated such relationships in moist soil aggregates. They show that the mass fractal model is applicable to such aggregates under the assumption of linear dependence of the fractal dimension and the unit size aggregate mass on the gravimetric water content.

Pores of different sizes present different microenvironments and habitats in soils. *Menendez et al.* have used soil thin sections and two-dimensional image analysis to subdivide the porosity of studied forest soils into distinct classes. Macroporosity and microporosity exhibit two different scaling fractal regimes that are separated at the threshold value of about 5 mm equivalent pore diameter.

Soil microrelief determines water infiltration, overland flow and drainage network development. Parameterization of soil surface roughness remains a challenging task. *Vidal Vázquez et al.* show that the scale dependence of roughness can be satisfactorily characterized with a fractal dimension and a reference variance. In field and laboratory experiments, fractal dimension values appeared to be always above 2.5, indicating anti-persistent behavior of soil surface roughness.

4.4. Other ecohydrologic systems

Techniques often depend on the component of the environment under study. This section of the special issue demonstrates the application of fractal methods to reveal and quantify scaling behavior in diverse ecohydrologic systems.

As the evidence of scale-dependency in transport processes in heterogeneous environments accumulates, it becomes important to understand what properties of the environmental variables affect this scaling. In a hydrogeological context, *Sivakumar et al.* have studied transport processes that occur in first order Markov chain-type structures, defined by transition probabilities between constituent facies. Their results indicate that transport scale dependence is affected by the number, proportion, and sequence of different facies.

Spatio-temporal data present a special challenge for uncovering scale dependencies. *Zhou et al.* have demonstrated how fractal models can be used to quantify scaling after removal spatio-temporal trends in rainfall data from a semi arid region.

5. Concluding remarks

This Special Issue contains just a small fraction of the scaling issues that must be dealt with in the description and modeling of soil and other environmental systems. As one moves across the hierarchy of scales, one encounters differences in the type of information obtained about the system, variables used to characterize the system, and the observed variability of the system. We concur with the authors of the special issue of Ecological Modeling on ecology of scale (Rietkerk et al., 2002) that there exists a need for clear understanding about the scales at which relevant processes operate when choosing an appropriate scale for observation and modeling. A recent example of how soil measurements can be simplified in an ecological model by accounting for scale can be found in Gyldenkærne and Jørgensen (2000).

Scaling of soil and hydrological properties and processes is a burgeoning field responding to the increasing need for environmental modeling and prediction. It is also being driven by progress in remote sensing technologies to estimate environmental parameters at large scales, by spatially intensive methods to measure indirect indicators of environmental physical properties, by new in situ measurement techniques to obtain small-scale data, and by the integration of georeferenced data collected at various scales (Pachepsky et al., 2003).

The proven viability of fractal models by no means makes them the ultimate approach for quantifying heterogeneity. Within the applicable range of scales, such models provide a balance between accuracy and clarity that may aid in gaining insight into sources and implications of the observed complexity. Once a greater insight into key processes is obtained, we expect processes causing apparent fractal scaling to be revealed and quantified.

The challenge of relating processes across scales is being met in ecology. Scale-invariant diversity measures are being developed (Yue et al., 2003). Cross-scale recursions in ecosystems are observed and interpreted within the hierarchy of scales (Ulanowicz, 1997; Jørgensen, 2000). Ecosystem regulation mechanisms operate over different time scales, and this complexity prohibits the repeated application of simple relationships (Jørgensen, 1999). Scaling relations in ecosystems can be interpreted as the result of self-organization. Juxtaposing scaling relations for biological systems with those observed in earth systems should lead to a better understanding of ecosystem functioning and interactions. It is our hope that this special issue will be instrumental in stimulating further studies on bridging scales in soils and ecohydrology.

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