Geoderma 287 (2017) 4–30

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Scale and scaling in soils

Yakov Pachepsky [a,*], Robert L. Hill [b]

[a] USDA-ARS Environmental Microbial and Food Safety Laboratory, 10300 Baltimore Ave., Bldg. 173, Beltsville, MD 20705, USA
[b] Department of Environmental Science and Technology, University of Maryland at College Park, College Park, MD 20742, USA

ARTICLE INFO

Article history:
Received 9 January 2016
Received in revised form 9 July 2016
Accepted 23 August 2016
Available online 9 September 2016

Keywords:
Hierarchy
Measurement metrics
Similitude
Power law
Dimension analysis
Spatiotemporal data

ABSTRACT

Scale is recognized as a central concept in the description of the hierarchical organization of our world. Pressing environmental and societal problems require an understanding of how processes operate at different scales, and how they can be linked across scales. Soil science as many other disciplines obtain the bulk of their empirical information at fine scales, whereas results of environmental diagnostics, monitoring, and predictions are needed to make important policy decisions at much larger scales. It becomes imperative to relate the information that is available and produced at different scales. The objective of this work is to present an overview of concepts that are currently used to define and relate scales in soil studies. The paper is not intended to be a compendium, but rather should be viewed as material for discussion, reference, and critique. It discusses definitions and terminology, including general approaches of scale problems in environmental studies that are applicable to soils, including hierarchies, measurement metrics, similitude, non-geometric scale metrics, and notions of upscaling and downscaling. Concepts of general scaling methods and theories are dimensional analysis, power law scaling, space and time dependent scaling. A section on spatiotemporal patterns introduces scaling ideas that were used in soil studies such as empirical orthogonal functions, data assimilation, and cumulative distribution function matching. Reviewed scaling methods developed specifically to soil studies include geometric similitude of pore spaces, scaling with Richards equation, scale dependencies of water and solute flux model parameters, scaling based on temporal stability, overland flow and sediment transport as the scaling phenomenon, and the relevance of scaling to pedotransfer functions. An outlook for scaling research in soils is presented that shows the needs of additional research and the feasibility of using scaling to enrich and advance soil research to help face the grand challenges of modern times.

Published by Elsevier B.V.

1. Introduction

Galileo Galilei was over 70 years of age, under house arrest, going blind, and stricken by the loss of his beloved daughter, but he somehow found the strength to write the book "**Two New Sciences.**" Pages after being written had to be smuggled abroad to be published by Elzevir in 1638 (Galilei, 1954). In this book, Galileo described one of his crowning discoveries – the existence of scale effects and scaling laws in Nature. He stated that "the properties which belong to figures that are merely geometrical and non-material must be modified when we fill these figures with matter and therefore give them weight." Galileo probably worked on scaling theory for a very long time and was using scaling ideas to help explain his observations on the increasing thickness of animal bones as the animals get larger, and to help explain why similar objects of different weights do not fall at the same velocity, but the lighter one lags behind. The new paradigm of scaling came to replace the belief that preservation of the geometric proportion guarantees proportional preservation of physical properties (Peterson, 2002).

Four centuries later scale is commonly recognized as a central concept in the description of the hierarchical organization of our world. Pressing environmental and societal problems require an understanding of how processes operate at different scales, and how they can be linked across scales. Many scientific disciplines obtain the bulk of their empirical information at fine scales, whereas the results of environmental diagnostics, monitoring, and predictions are needed to make important policy decisions at much larger scales (Bierkens et al., 2000). It becomes imperative to relate information available and produced at different scales.

Environmental phenomena, such as climate change, regional deforestation, and regional water redistribution cannot be elucidated at a single scale of observation. An understanding of how processes operate at various spatial scales and how they can be linked across scales becomes a primary goal when investigating these and many other complex phenomena (O'Rourke et al., 2015). Specific management effects, i.e. agricultural management effects on crops, can often be best observed only at a range of scales.

* Corresponding author.
E-mail address: yakov.pachepsky@ars.usda.gov (Y. Pachepsky).

http://dx.doi.org/10.1016/j.geoderma.2016.08.017
0016-7061/Published by Elsevier B.V.

Distinct breaks or thresholds in systems representation can be found that correspond to specific levels of organization within a hierarchical system. It is necessary to identify these scale thresholds, and to derive the appropriate descriptions of interactions between system elements and system environments taking place within and between the levels of organization.

Scale has moved to the center of obtaining and disseminating experimental and monitoring information. The multidisciplinary research in the environmental arena includes representatives of different sciences that have different spatial and temporal scales of investigations (Dalgaard et al., 2003). Harmonizing their results require procedures and methods of scaling up and scaling down. The translational science that moves research advances to the applications has outscaling as one of its essential research fields Translating the knowledge to managers, policy makers, and the public presumes upscaling the information, as most of the knowledge that is applied has been obtained at low-resolutions (Davis and Bigelow, 2003).

As we have entered the era of "big data", the tremendous development of data collection means creates new challenges and opportunities in understanding scales and applying this understanding. Scaling is the essential element of condensing large volumes of data into usable information. Conversely, large volumes of data at different scales will inevitably lead to a better understanding of the relationships between the system representations at different scales so as to provide an overview of concepts and methods.

The objective of this work is to present an overview of concepts that are currently used to define and relate scales in soil studies. The paper discusses definitions and terminology, general approaches of scale problems in environmental studies that are applicable to soils, and the scale transfer techniques that have been developed specifically in soil research. It is not intended to be a complete compendium, but rather as material for discussion, reference, and critique.

2. Definitions and terminology

Scale is a vague term having multiple connotations. Scale definition and scale concepts have long been a topic for debate in natural sciences. There is no commonly accepted single definition, and yet the term is used liberally (Jenerette and Wu, 2000). The same reference to scale, however, may have very different meanings. For example, research at "field scale" may mean research done outside of the laboratory, it may mean research within the extent of a field, or it may mean research using field plots without any reference to a specific field, etc.

There appear to be three major ways to decrease the ambiguity in terminology related to scales. One way is based on hierarchies and the other two ways are based on metrics related to measurements.

2.1. Scale definitions via hierarchies

Hierarchical definitions of scales stem from perceptions developed in a particular scientific or engineering discipline. Examples of scale hierarchies are shown in Fig. 1. These hierarchies have some common features. The organizational hierarchy describes at which level a natural system is studied. Each level can be regarded as a system by itself, with its own terminology, and can be seen as a combination of subsystems at lower levels or as a subsystem of higher level systems. Each level represents the nature and variability of systems from the level below. The multitude of "sub-wholes" termed holons represents each hierarchy level. One suggested set of holons for soils includes crystals/grains, microaggregates, macroaggregates, horizons, pedons, and soil associations (Wagenet, 1998).

Differences among the hierarchy levels are profound and consequential. Different information is obtained about the system at different levels. For the example of hierarchy of soil systems in Table 1, soil studies at the molecular level may inform about the adsorption of chemicals, investigations at the aggregate level provide data on soil micromorphology and structure formation, whereas research at the horizon level can lead to characterization of mass transfer, weathering, and organic matter accumulation.

In general, for a given hierarchy level, studies at the lower levels may reveal more detail about the mechanisms of this level functioning, whereas studies at the higher levels reveal constraints for this functioning. Research possibilities and study designs change as the hierarchical level of research changes. Table 2 illustrates such changes for the case of ecological studies. In general, more complexity can be captured at the lower levels of hierarchy (Fekete et al., 2010).

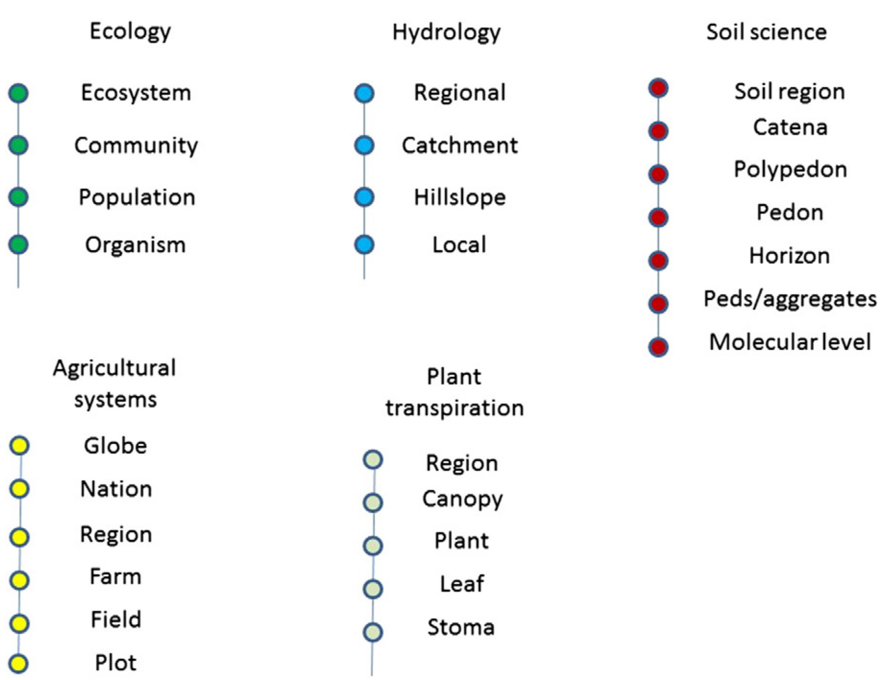

Fig. 1. Examples of scale hierarchy used in scientific disciplines and interdisciplinary studies. The suggested levels of hierarchy are shown for ecology (Rabbinge, 1997), hydrology (Blöschl and Sivapalan, 1995), soil science (Hoosbeek and Bryant, 1992), agricultural systems research (Rabbinge, 1997), and plant transpiration research (Jarvis and McNaughton, 1986).