Geoderma 160 (2010) 64–73

Contents lists available at ScienceDirect

Geoderma

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

Multifractal analysis of Hg pore size distributions in soils with contrasting structural stability

J. Paz Ferreiro *, E. Vidal Vázquez

Facultad de Ciencias, Universidade da Coruña, 15071, Coruña, Spain

ARTICLE INFO

Article history:
Received 12 January 2009
Received in revised form 26 October 2009
Accepted 21 November 2009
Available online 16 December 2009

Keywords:
Multifractal analysis
Pore size distribution
Mercury injection
Structure stability
Simulated rainfall

ABSTRACT

Parameters are needed to recognize and monitor changes in pore size distributions (PSD) caused by factors such as differences in soil management systems or by disturbance of the soil structure. The objectives of this work were to evaluate the potential of multifractal parameters obtained from mercury injection porosimetry (MIP) curves to distinguish between two soils with contrasting structure stability indices and between distinct stages of the surface of these soils. Samples were collected from the uppermost surface layer of two agricultural soils, before and after simulated rainfall. The first soil was loamy textured, with 4.61% organic matter content and a mean weight diameter (MWD) of 2.136 mm. The second soil was a silty loam with 2.17% organic matter content and a MWD of 0.262 mm, highly susceptible to crusting. Crusted soil surfaces were produced by cumulative 260 mm and 140 mm simulated rainfall on the loamy and the silty loam soil, respectively. Ten replicated samples from the initial freshly-tilled and the crusted soil surfaces were analyzed. In the diameter range of 100–0.005 µm, the freshly-tilled surface of the loamy soil had a significantly ($p<0.05$) higher pore volume than its rain-disturbed counterpart, whereas the respective pore volume of the silty loam soil slightly increased following simulated rain. The scaling properties of PSDs measured by MIP could be fitted reasonably well with multifractal models. Generalized dimension spectrum, D_q, led to a better definition of multifractal scaling than singularity spectrum, $f(\alpha)$. Multifractal parameters such as Hölder exponent of order zero, α_0, aperture of the left part of the singularity spectrum ($\alpha_0-\alpha_{q+}$), entropy dimension, D_1, correlation dimension, D_2, as well as indexes (D_0–D_1) and (D_0–D_2) were significantly different between the structurally stable loamy soil and the silty loam soil prone to crusting and between initial and rain-disturbed surface stages ($p<0.05$). Moreover, D_1 and (D_0–D_1) were also significantly affected by the interaction between soil type and surface stage. Parameter α_0 ranked as: loam initial < loam rain-disturbed < silty loam initial < silty loam rain-disturbed, whereas the opposite rank was true for entropy dimension, D_1. Consequently, low structural stability or stability decay due to disaggregation by rainfall lead to clustering of PSDs measured by Hg intrusion porosimetry. These results show that multifractal analysis of PSDs may be an appropriate tool for characterizing soil structure stability and also a suitable indicator for assessing soil surface evolution stages.

1. Introduction

The pore size distribution (PSD) of a soil depends on the combined effects of soil texture and structure. The frequency distribution of pore sizes in the soil controls water and air storage, their movement and transport into the profile and their transmission to plant, atmosphere or groundwater bodies, and affects the extent to which soil organisms are able to occupy pore space. As an attribute depending on soil structure, soil porosity is affected by changes in water content, causing shrinking–swelling, temperature which bring about freezing–thawing, biological activity and management practices. It is also vulnerable to externally imposed destructive forces (Dexter, 1988; Díaz-Zorita et al., 2002).

The soil pore system has been classified according to various criteria, mainly pore size and pore function. The simplest classification scheme recognizes three categories of soil pores: micropores, mesopores or capillary pores and macropores (Pini et al., 1993). However, when classifications are based on pore dimensions, various thresholds and different terms have been used to describe the soil pore space (Dexter, 1988; Ehlers et al., 1995). Early approaches for soil pore space analysis take into account pore origin, instead of just pore size (Childs, 1969; Monnier et al., 1973). Although pore space is continuous, two main types of soil pores can be distinguished: a) structural pores, which result from biological activity, climate, tillage and traffic effects, and b) textural pores, which result from the packing of soil elementary particles. Inter-aggregate and intra-aggregate soil porosities have been used to designate the dual soil pore system, but these categories do not always match the structural and textural pore space, respectively (Fiès, 1992).

Greenland (1981) distinguished three pore size categories: i) transmission pores (>50 µm) responsible for water flow during drainage, ii) storage pores (50–0.5 µm) retaining most available water and iii) residual pores (<0.5 µm) where chemical reactions occur. These criteria show a rough correspondence with soil hydraulic properties and

* Corresponding author. Tel.: +34 981 167000; fax: +34 981 167065.
E-mail address: jpaz@udc.es (J. Paz Ferreiro).

0016-7061/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.geoderma.2009.11.019

were frequently used later on (Ehlers et al., 1995; Pagliai et al., 2004; Vidal Vázquez et al., 2008).

Because soil pores may range from sizes larger than 10^3 μm to sizes smaller than 10^{-3} μm, there is no single determination method covering the whole domain of pore scales of soil structural units. Direct methods have obvious advantages as they allow quantification of the pore space in terms of shape, size, continuity and arrangement (Díaz-Zorita et al., 2002). Different instruments, for example a conventional camera or confocal microscope, are commonly used to analyze images of soil sections; the former allows assessment of soil pores larger than 30 μm (Ringrose-Voase and Bulock, 1984), whereas the latter gives information about pore sizes with a resolution of a few micrometers (e.g. Dathe et al., 2006). Computed tomography provides 3D images of soil pores using rapid and non-destructive procedures (e.g. Hopmans et al., 1994). Nowadays, the use of high-resolution scanners allows the characterization of macro- and mesopore scales with a voxel resolution down to a few micrometers (e.g. Lee et al., 2008). This notwithstanding, there is a need to analyze the array of pore sizes below this threshold, because of its important functions. For instance, assessing the PSD range that retains available water means the determination of those pores with an equivalent diameter between 0.2 and 20 μm, approximately (Pagliai et al., 2004).

Frequently, PSDs are obtained by indirect methods that rely on the evaluation of parameters related with pore sizes and/or volumes, even if these methods provide little information on pore geometry. The water retention curve is the most widely acknowledged method used to estimate PSDs. Mercury injection porosimetry (MIP) also has been recognized as an useful tool for characterizing the inter-aggregate porosity, from about 100 to 0.005 μm, which includes all the textural compartments and the smaller classes of the structural domain (e.g. Fiès, 1992; Pini et al., 1993; Pagliai et al., 2004). The main drawback of the MIP technique lies in that it gauges the circular pore entrance radius, not the actual pore dimensions. Hence, there is some bias in the MIP results, and reported pore sizes are smaller than they actually are (Fiès and Bruand, 1998; Bartoli et al., 1999).

Fractal geometry aims at describing complex geometrical objects, while multifractal analysis characterizes complex (singular) statistical distributions. When a Pareto or exponential law is used to explain the PSD the exponent can be interpreted as the fractal dimension of a certain geometrical object (Mandelbrot, 1983). Fractal models such as the pore-solid fractal model (PSF) (Rieu and Perrier, 1998; Perrier et al., 1999) have been widely applied in soil science. Interest has recently turned to multifractal analysis of porous media. The use of multifractal tools to understand soil porosity means that the PSD can be viewed as a singular statistical distribution and it is reasonable to explain it as a multifractal measure (Caniego et al., 2001).

Pore size distributions measured by MIP have been proven to be fractal in a limited range of scales (Bartoli et al., 1991; Pachepsky et al., 1995, 1996). Also, PSDs determined by two combined methods, for example, MIP and adsorption isotherms (Jocefaciuk et al., 2001) or MIP and water retention curves (Bartoli et al., 1999; Gomendy et al., 1999), demonstrated the fractal nature of soil porosity. A multiscale model of soil structure, the PSF model (Perrier et al., 1999), associated both a fractal pore-number size distribution and a fractal solid number size distribution by incorporating a third phase, the interface, that is intermediate between the pore and solid phases. This allows a relation to be derived between the scaling behavior of the mass of soil pores, the mass of the solid matrix and the interface between them. The analysis of PSDs obtained from image analysis by means of multifractal formalism has been introduced by Caniego et al. (2001, 2003) and Posadas et al. (2003) and this approach has been used by many authors (e.g. Dathe et al., 2006; Grau et al., 2006). Multifractal analysis of MIP data sets has been recently performed (Vidal Vázquez et al., 2008).

A multifractal, or, more precisely, a geometrical multifractal is a non-uniform fractal that unlike a uniform fractal exhibits local density fluctuations. Geometrical multifractals can be decomposed into many (possibly infinite) subsets characterized by different scaling exponents. Thus, multifractals are intrinsically more complex and inhomogeneous than uniform fractals. Although monofractals are well characterized by a single fractal dimension, multifractals no longer possess global scale invariance. Multifractal analysis relies on the determination of the scaling properties of the data set studied which are summarized by the multifractal spectrum (Everstz and Mandelbrot, 1992). However, there are different types of multifractal spectra which are computed using different algorithms. Therefore, it makes sense for experimental data sets to explore if any of the methods applied lead to a well defined spectrum, which means checking that the corresponding dimensions have a suitable scaling behavior.

There is no simple definition of soil structure stability, so it is accepted that this term is not completely objective and often relies on a specific measurement technique. Most descriptions of soil structure refer to the arrangement of elemental particles and the pores between then or are based on the stability of soil fragments after application of mechanical stress (Dexter, 1988; Díaz-Zorita et al., 2002). Aggregate stability at any time results from the balance between the forces or processes promoting aggregation and those causing its breakdown (Le Bissonnais, 1996; Díaz-Zorita et al., 2002). This notwithstanding, quantitative characterization of the soil structure is currently achieved by measuring aggregate sizes. Other methods are based on the determination of mechanical properties or the permeability of fluids (Dexter, 1988; Pagliai et al., 2004).

Assessment of the aggregate size distribution of a soil at any particular moment may not suffice to portray the dynamic nature of soil structure (Darboux and Le Bissonnais, 2007). The challenge is to characterize the inherently unstable nature of the soil structure and its vulnerability to destructive forces. Aggregate size distribution has a bearing on soil pore size distribution. Therefore, both pore space distribution and aggregate stability indexes are viewed as complementary methods for characterizing soil structure (Dexter, 1988; Díaz-Zorita et al., 2002).

This work is an extension of a previous investigation by Vidal Vázquez et al. (2008). PSDs of aggregates sampled on the freshly-tilled and the crusted surface of a loamy soil showed multifractal behavior. Moreover, multifractal parameters were able to discriminate between the two contrasted structural stages sampled in this soil. Following this approach, here we compare the previously studied loamy soil and a silty loam soil characterized by high and low structural stability, respectively, and therefore, distinct susceptibility to crusting. In each soil two contrasted structural stages, i. e. a freshly-tilled soil surface and its crusted counterpart produced by raindrop impact, were studied. The main objective of this work was to evaluate the potential of the multifractal analysis for distinguishing between PSDs of soils with marked differences in structural stability indices. In addition, the multifractal formalism was used to further compare contrasted evolution stages of the soil surface.

2. Material and methods

2.1. Study site and sampling

Two medium textured soils were collected from agricultural experimental fields located in Coruña, Galicia, Spain. The first soil, sampled at Pazo de Lóngora (43°26′12″ latitude, 8°23′46″ longitude), was loamy textured. The second soil, sampled at Centre for Agricultural Research (CIAM) at Mabegondo (43°14′26″ latitude, 08°15′8″ longitude), was a silty loam. These soils were classified as Humic Dystrudept (Soil Survey Staff, 2006). The loamy soil was characterized by both high organic matter content and structural stability. The silty loam soil had low organic matter content and its structure was rather unstable (Table 1). Therefore, loamy and silty loam soils will be referred to as high and low aggregate stability soils, respectively.