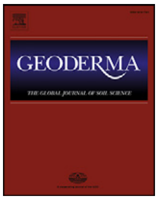
Geoderma 287 (2017) 147–156

Contents lists available at ScienceDirect

Geoderma

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



Relation between soil forming factors and scaling properties of particle size distributions derived from multifractal analysis in topsoils from Galicia (NW Spain)

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ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form 11 July 2016
Accepted 4 August 2016
Available online 16 August 2016

Keywords:
Soil particle size distribution
Multifractal analysis
Partial Least Square Regression
Soil forming factors

ABSTRACT

Soil particle size distribution has been previously shown to behave as a multifractal. In this study, we analyzed the relation between soil forming factors and several multifractal parameters derived from generalized dimension and singularity spectra calculated from particle size distribution of soils from Galicia (NW Spain). A number of 187 samples were collected from the upper horizon (0–30 cm depth) of soils located in different parts of the region, covering a wide range of parent materials, climatic conditions and land use. Particle size distributions of fine earth fractions (<2 mm) were measured using a laser particle analyzer that yielded a number of data points per sample between 85 and 161. Rényi and singularity spectra were calculated for each sample and parameters D_{max}, D_{min}, D_{max}–D_{min}, D_0, D_1, D_2, and D_1/D_0 of the Rényi spectra, and α_{max}, α_{min}, α_0, $f(\alpha_{max})$, $f(\alpha_{min})$, α_{max}–α_{min}, α_{max}–α_0, and α_0–α_{min} of the singularity spectra were extracted. The spatial distribution of the multifractal indices and their relation with soil forming factors were predicted using a PLS approach with climate, geology, land use and topography as covariates. The accuracy of the estimates was evaluated by cross-validation upon the same set of samples. The performance of the model was relatively good in the case of D_1 ($R^2 = 0.50$, RMSE $= 0.02$). As a result, the heterogeneity of particle sizes in topsoils from Galicia can be partly explained by a combination of climatic factors, land use and geology. Parent material and some climatic indexes were the most influential variables explaining the scaling properties of particle size distributions.

1. Introduction

Particle size distribution (PSD) is one of the key soil properties that determine many of the other chemical, physical, and biological properties. Its importance for soil functioning was understood as early as the beginning of last century, when PSD was usually described using the term texture. In these early days, Wilder (1905) identified soil texture as one of the variables influencing apple production. Around that time, texture was recognized as a key soil property determining water availability for crops (Stewart, 1927), and soil structure. Nowadays, soil texture is considered one of the key soil properties influencing many soil properties like soil aggregation and structure (Benhur et al., 1985; Chepil, 1953; Hubbell, 1951; Jones, 1983; Keller and Dexter, 2012), hydraulic conductivity and permeability (Benhur et al., 1985; Kemper and Noonan, 1970; Mamedov et al., 2001; Saxton et al., 1986; Wosten and Vangenuchten, 1988), water holding capacity (Miller and Aarstad, 1973; Stewart, 1927; Vereecken et al., 1989), erodibility (Chepil, 1953), crop productivity (Arora et al., 2011; Davis et al., 1968; Tremblay et al., 2012), nutrient availability and recycling (Nash and Johnson, 1967; Nassi o Di Nasso et al., 2015; Walters et al., 1992; Ziadi et al., 2013), soil biology (Bach et al., 2010; Cable et al., 2008; Chau et al., 2011; Thomsen et al., 1999), carbon storage and turnover (Hassink, 1992; Jindaluang et al., 2013; Rutherford and Juma, 1992; Silver et al., 2000; Thomsen et al., 1999), gas exchange with the atmosphere (Brye et al., 2013; Gu et al., 2013) and many geochemical processes (Bai et al., 2012; Brye et al., 2013; Hook and Burke, 2000; Rodríguez et al., 2008).

Nowadays, texture is still the most common descriptor of PSD used by scientists and engineers. It refers to the proportions of three particle size classes (sand, silt and clay) present in the *fine earth* fraction of the soil (those particles with size <2 mm). The limits that separate these three fractions are somehow arbitrary, and vary from one soil classification system to another. The proportions are usually plotted in a texture triangle, where the soil textural class is identified. Although its use is widespread, this description of PSD is rather imprecise, since it ignores the distribution of sizes inside each class, and even each textural class includes soils with different proportions of sand, silt and clay.

The most common methods to classify soil particles according to their size were traditionally based on a combination of techniques that include sieving and sedimentation (Gee and Bauder, 1986). Sieves of different mesh-sizes are used to separate big particles, usually

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http://dx.doi.org/10.1016/j.geoderma.2016.08.005
0016-7061/

classified as sand, while fine particles (silt and clay) are separated taking advantage of the different sedimentation velocities of particles in suspension according to their size. The nature of these methods makes the separation of particles in many size fractions impractical, and therefore their number is usually limited to 3 or 5. To overcome this limitation, more accurate description of PSD than texture classes were attempted using mathematical models to describe PSD. These models assume PSDs following lognormal, bimodal, bimodal lognormal, exponential, or power law distributions (Buchan et al., 1993), and their performance depends on soil texture type (Hwang et al., 2002).

In recent times, technical advances using laser diffraction techniques in particle size analysis have been introduced in soil studies, yielding PSD measurements with more particle size classes. These methods use Fraunhofer theory to calculate the size of suspended particles as a function of the angle of light scattering when a laser beam passes through a suspension. Contrarily to the sieving-sedimentation methods, which yield mass composition, the laser diffraction techniques deliver particle volume compositions. Therefore, the results obtained using both methods differ (Buurman et al., 2001; Polakowski et al., 2015; Taubner et al., 2009), especially as clay content of the soil increases (Polakowski et al., 2015; Yang et al., 2015).

The increase of the number of size intervals in PSD has allowed the use of fractal geometry to explain changes in the distribution of a measure (particle mass, volume or number) as a function of the scale (particle size). Initially, fractal description of PSD assumed a scaling behavior that could be explained by one single power law or fractal dimension, in what is considered a monofractal (Tyler and Wheatcraft, 1992; Xia et al., 2015). However, this approach can only be applied within a certain range of particle sizes, which varies from soil to soil (Filgueira et al., 2006; Grout et al., 1998; Tyler and Wheatcraft, 1992), and therefore the idea of PSD fractal scaling has to be expanded to consider PSD measures as a multifractal. The first attempt to do so was proposed by Grout et al. (1998), who demonstrated the multifractal characteristics of three horizons of a soil profile from US. Expanding this idea, Posadas et al. (2001) analyzed the scaling properties of PSD in 30 soils from USA, Brazil and Switzerland, covering a wide range of textures, and found that only soils with clay contents below 10% behaved as monofractals, while all the rest showed multifractal behavior.

Several authors have used multifractal analysis to characterize soil PSD obtained with laser diffraction techniques (Martín and Montero, 2002; Miranda et al., 2006; Montero, 2005; Montero and Martín, 2003; Paz-Ferreiro et al., 2010; Peng et al., 2014). For example, Miranda et al. (2006) found multifractal behavior in the PSD of Brazilian Ferralsol saprolites subjected to different reclamation treatments, and found that some parameters derived from generalized dimension and singularity spectra showed significant differences between treatments. Wang et al. (2008) used multifractal analysis to characterize PSD from soils under different land uses and found a correlation between several multifractal parameters of particle size composition and soil organic matter. Paz-Ferreiro et al. (2010) observed the potential of multifractal analysis of PSD to discriminate between samples belonging to the same textural class and to differentiate between soil management practices. Wang et al. (2015) found that PSD of reconstructed soils in coal mine dumps showed multifractal behavior.

The composition of mineral particles in a soil horizon is assumed to be the result of weathering of the parent material by the concomitant action of other soil forming factors (climate, topography, time and organisms). During the different stages of pedogenesis, particles of primary minerals are weathered while particles of secondary minerals are being formed. These processes determine the composition and size distribution of particles in soils. For example, it is well known that a warm and humid climate yields soils with an enrichment in fine particle fractions as compared to dry or cold climates. Similarly, parent materials more resistant to weathering, like quartzites, evolve to soils with higher amount of coarse particle fractions compared to more weatherable parent materials like amphibolites. The topographic position of a soil is also controlling its PSD, since erosion and transport of fine materials produce an enrichment of fine particle fractions from the upper part of a hillslope towards the foothill. These relations between particle sizes and soil forming factors have been conducted separating particles in just few size classes, but their action must be reflected on the scaling properties of PSD, and more precisely, in the multifractal behavior of PSD.

Despite the proven suitability of multifractal analysis to characterize soil PSD, few studies have tried to relate the scaling properties of particle sizes in soils with soil forming factors, and they were focused mainly on the effect of different land uses. It is hypothesized that multifractal parameters, as indices that can describe the scaling properties of PSD, must be related to the different soil forming factors.

2. Material and methods

2.1. Study area

This study was conducted in the autonomous region of Galicia (NW Spain, Fig. 1), a transitional area from oceanic hyper-humid to subhumid conditions and a wide range of lithologies from hyperacid (quartzites) to ultramafic (serpentinites) rocks. Soils are generally shallow or of moderate depth, characterized by low fertility, high to moderate acidity (pH 4.4–5.5), low effective cation exchange capacity and base saturation, and high amounts of exchangeable Al. Organic matter content is usually high, with an umbric epipedon rich in organo-aluminium complexes commonly present, followed by an underlying cambic horizon (Umbrisols), while Leptosols and/or Regosols are found in areas prone to erosion. Soils developed on mafic rocks and their transformations (amphibolites, gabbros, eclogites) may show andic properties and high amounts of reactive-Al and short-range ordered sesquioxides, which form Al-humus complexes that stabilize organic compounds (Verde et al., 2005). In stable areas, such as those with Tertiary and Quaternary sediments and easily weatherable materials, soils can show ferralic properties. In general, soil textures vary from sandy, in soils developed on granites, through loamy, in soils developed from schists and slates, to loamy clay and clay in soils developed on limestones, mafic, and ultramafic rocks.

2.2. Sampling scheme and particle size analysis

A total number of 187 georeferenced soil samples from epipedons (0–30 cm depth) was used in order to construct a sample database covering the entire study area (Fig. 1). For this purpose, samples collected using two sampling schemes were merged together: i) samples collected using a regular grid of 16 × 16 km, which covered most of the study area; and ii) georeferenced samples collected following a random scheme, available from previous studies. This set of samples captures a large range of the climatic conditions, geologic materials and land-use types within the region. In each sampling location, a composite sample was collected comprising 8 subsamples randomly located within a radius of 20 m from a central point that represented the sampling location, all under the sample parent material and land use. The samples were collected using a hand auger and the location was recorded using a global positioning system (GPS) receiver. Samples were transported to the laboratory, air-dried, and sieved through a 2-mm mesh to obtain the *fine earth* fraction before analysis.

Particle size distributions were measured using a laser diffraction method. Samples were introduced in a laser particle analyzer Micromeritics Saturn DigiSizer® II. A weight of 5 g of each sample was suspended in distilled water and dispersed using ultrasounds prior to the measurement of PSD. Although the description of the instrument indicates that PSDs can be measured in the range 0.01–2000 μm, errors in the measurement of the amount of sand particles are unavoidable due to the slower transit of big particles compared to small ones along the circulation circuit (Beuselinck et al., 1998; Polakowski et al., 2015). Therefore, the measurements were deliberately limited to particle