Geoderma 317 (2018) 39–46

Contents lists available at ScienceDirect

Geoderma

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

Integrating multi-fractal theory and geo-statistics method to characterize the spatial variability of particle size distribution of minesoils

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ARTICLE INFO

Handling Editor: A.B. McBratney

Keywords:
Geo-statistics
Multi-fractal
Spatial variability
Soil particle distribution
Opencast coal-mine

ABSTRACT

Opencast coal mining activities trigger considerable alteration of soil structure, and characterizing the spatial variability of soil particle size distribution (PSD) quantitatively can contribute to understand mined soil properties and perform mined land rehabilitation. In this study, a novel method combining multi-fractal and geo-statistics was used to quantify the spatial variability of PSD in an inner dump after dumping and before reclamation in the Shanxi Pingshuo Antaibao opencast coal-mine of China. Soil samples were collected from the depths of 0–20 cm and 20–40 cm at 78 sampling sites in the study area over an area of 0.44 km^2. Five multi-fractal parameters (i.e., $D(0)$, $D(1)$, $D(1)/D(0)$, $\Delta\alpha$, and $\Delta f(\alpha)$) of PSD of minesoils were calculated, and geo-statistics was used to demonstrated the spatial variability of multi-fractal parameters of PSD of minesoils. An expression quantifying spatial variability degree of PSD of minesoils was proposed. This novel method exhibited more advantages in characterizing variability of PSD of minesoils compared to single multi-fractal or geo-statistics method, and it can quantify the variability of whole PSD characteristics in detail, including PSD range, PSD concentration degree, PSD dispersion degree, PSD non-uniformity and PSD symmetry degree. PSD of minesoils basically presented a moderate spatial variability according to the method combining multi-fractal and geo-statistics, and opencast mining activities didn't give rise to severe spatial variability. This study provided a valuable reference for characterizing the spatial variability of soil PSD.

1. Introduction

Moving operation of soils and rocks carried out during opencast coal mining can trigger considerable alteration of soil structure, resulting in the degradation of soil physical properties in newly constructed soils (Zhang et al. 2015). Differences in soil physical condition must be adequately understood and quantified to perform meaningful classification and utilization, particularly these artificial soil structures that are quite different from currently recognized structures (McSweeney and Jansen 1984). As one of the most important physical attributes, particle size distribution (PSD) reflects soil particle composition and has great influence on soil properties related to soil structure (Wei et al. 2015). PSD is widely used in soil classification and in estimating soil hydraulic properties (e.g., soil water retention curve, soil hydraulic conductivity and soil bulk density) (Antinoro et al. 2014; Filgueira et al. 2006; Hollis et al. 2012; Hwang et al. 2011). Therefore, quantifying the spatial variability of PSD of reconstructed soils can contribute to understand minesoil properties in detail and perform precise land rehabilitation in mining area.

Geo-statistics offers a set of tools to quantify spatial characteristics in various natural phenomena (Long et al. 2014; Oliver 1987), as well as the spatial variability of soil properties (Cambardella et al. 1994; Trangmar et al. 1985; Tripathi et al. 2015), and which can be defined as an useful approach for characterizing and predicting the spatial structure of geo-referenced variables. Soil PSD refers to the proportion of different soil particles in soil solid, which is usually expressed using any particle size and its corresponding cumulative percentage content curve. Compared to other soil attributes, the PSD characteristics of one soil sample cannot be quantified as a specific numerical value. Little research has been conducted in applying geo-statistics to quantify the spatial variability of soil texture, including anthropogenic soils (Wang et al. 2017b) and natural soils (Li et al. 2014; Rosemary et al. 2017). However, the geo-statistics method only reflects the variability of sand content, silt content and clay content, and it can't exhibit the spatial variability of entire PSD in detail. Therefore, it is infeasible to use single geo-statistics to characterize the spatial variability of PSD of minesoils comprehensively.

Fractal geometry is a useful tool for quantifying complex natural

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https://doi.org/10.1016/j.geoderma.2017.12.027
Received 12 August 2017; Received in revised form 13 December 2017; Accepted 20 December 2017

phenomena such as soil/rock physics (Gimenez et al. 1997; Grout et al. 1998). Fractal dimension from simple fractal method is widely used in disclosing the scaling domains of PSD and reflecting the degree of uniformity of soil texture (Filgueira et al. 2006; Tyler and Wheatcraft 1992). For example, Gao et al. (2016) found fractal dimension was significantly positive correlated with clay and silt contents and significantly negative correlated with sand content, and which was a reliable and quantitative parameter to monitor soil environment changes; Su et al. (2004) noted that fractal dimension can be used to describe PSD characteristics and its relationship with land desertification; Zhao et al. (2016) characterized the PSD of soils (0–500 cm) across the typical loess zone of China and analyzed the regional spatial distribution patterns of PSD using fractal dimension.

A closer look at spatial series of nature phenomena often show "bursts" and "jumps" and, in general, the erratic variation cannot be explained using a simple fractal dimension (Grout et al. 1998; Wang et al. 2016). Multi-fractal analysis can determine the measure of soil particle mass of characteristic size in each region or subinterval (Posadas et al. 2001; Sun et al. 2016); recently, it has been used to characterize spatial variation of soil PSD. For example, Wang et al. (2008) used multi-fractal method to characterize PSD in soils with the same taxonomy and different land-use types; Wang et al. (2015b) analyzed the PSD from four modes of soil reconstruction in the Shanxi Pingshuo Antaibao opencast coal-mine dump using multi-fractal theory. However, multi-fractal method has its disadvantage in characterizing soil PSD, and it only can quantify the spatial variability of soil PSD in specific one soil sample and can't reflect the variation in a large scale (Li et al. 2011; Paz-Ferreiro et al. 2010; Wang et al. 2008).

Therefore, using single geo-statistics method or multi-fractal theory can't characterize the spatial variability of PSD of minesoils comprehensively. The objectives of our study were to (i) collect PSD data of soil profiles in opencast mining area, (ii) create a new approach characterizing spatial variability of soil PSD based on multifractal theory and geostatistics method, (iii) analyze the spatial variability of PSD of minesoils quantitatively and discuss the effects of opencast coal mining activities on soil PSD characteristics.

2. Materials and methods

2.1. Study area

The study area was an opencast coal-mine in Shanxi Pingshuo, which is the largest opencast coal mining area in China, including the Antaibao, Anjialing and East opencast mines. The Pingshuo opencast coal-mine is located along the border of Shanxi Province, Shaanxi and Inner Mongolia of the east Loess Plateau, with geographic coordinates of 112° 17′ 28″~113° 28′ 10″ E, 39° 25′6″ ~ 39° 36′5″N, as shown in Fig. 1.

This mining area has a typical temperate arid to semi-arid continental monsoon climate and a fragile ecological environment. The average annual rainfall is approximately 450 mm, with 65% falling from June to September. The average annual evaporation, however, is approximately 2160 mm, 4.6 times more than the rainfall. Its chestnut soils are characterized by low levels of organic matter. The extensive mining activity resulted in the fragile eco-environmental conditions to worsen in this area (Wang et al. 2013; Zhao et al. 2013).

The specific study area was located in an inner dump of the Antaibao mine with an area of 0.44 km^2. The study site was on the top platform of the inner dump, with an altitude of 1474–1480 m. It was dumped in 2012 and no vegetation was planted.

2.2. Soil sampling and analysis

In June 2013, 156 soil samples were equally collected using an auger from 0 to 20 cm and 20–40 cm depths at 78 sampling sites in the study area (Fig. 2). The sampling sites were randomly arranged within a distance of 60–80 m. All soil samples were air-dried, and the clods were broken using steel rolling pins to pass through a 2-mm mesh. Soil particles of soil samples were analyzed using a laser particle-size analyzer - Longbench Mastersizer2000 (Malvern Instruments, Malvern, England). PSD was classified based on clay ($<$0.002 mm), silt (0.002–0.05 mm) and sand (0.05–2 mm) contents as in the soil taxonomy developed by U.S. Department of Agriculture (USDA). According to this classification, the soil texture of the study area was silty loam.

2.3. Multi-fractal analysis of soil particle size distribution

The length of the intervals $I = [0.02, 2000]$ supplied by the laser particle-size analyzer followed a logarithmic scale. A new dimensionless interval $J = [0, 5]$ was built by making the following transformation.

$$\varphi_i = \lg(\phi_i/\phi_1),\ i = 1, 2, \ldots, 100 \tag{1}$$

where ϕ_i is soil particle size measured using laser particle-size analyzer in μm, $\phi_1 = 0.02$ μm, φ_i is the dimensionless value after the soil particle size made equidistant subintervals conversion.

A number $N(\varepsilon) = 2^k$ of cells of equal size $\varepsilon = 5 \times 2^{-k}$ for k ranging from 1 to 6 were considered in the interval J. $p_i(\varepsilon)$ was defined as the probability of finding soil particles of a certain mass within particle size interval J_i (Guan et al. 2007; Wang et al. 2015b).

The multi-fractal behavior of a measure p with $p_i(\varepsilon)$ as the mass percentage of soil particles of characteristic size in subinterval may be represented using the generalized dimensions, and which were computed using following expression (Grassberger 1983).

$$D(q) = \lim_{\varepsilon \to 0} \frac{1}{q-1} \frac{\lg\left(\sum_{i=1}^{N(\varepsilon)} p_i(\varepsilon)^q\right)}{\lg \varepsilon} \tag{2}$$

for $q \neq 1$, and.

$$D(1) = \lim_{\varepsilon \to 0} \frac{1}{q-1} \frac{\lg\left(\sum_{i=1}^{N} p_i(\varepsilon) \lg p_i(\varepsilon)\right)}{\lg \varepsilon} \tag{3}$$

for $q = 1$. Where q is any real integer. Parameter q acts as a scanning tool scrutinizing the denser and rarer regions of the measure p.

The generalized dimensions for $q = 0$ and $q = 1$ are known as capacity dimension, $D(0)$, and entropy dimension, $D(1)$. The capacity dimension is known as the box-counting dimension and provides average information of a system, and it can characterize soil PSD range. The $D(1)$ is related to the information or Shannon entropy, and it quantifies the concentration degree of soil PSD (Miranda et al. 2006; Wang et al. 2008).

Then, the set of points defined by $(q, D(q))$ as q varies, defines a curve that depicts the generalized spectrum of the measure p. In general, this spectrum is a decreasing function of q with a sigmoidal shape (Montero 2005). Therefore, the most heterogeneous case gives $D(0) = 1$, as it has the richest soil textural structure, whereas the most homogeneous distribution satisfies $D(0) = 0$. On the other hand, a $D(1)$ value close to 1 also demonstrates evenness of measures over the sets of cell size, whereas a $D(1)$ close to 0 reflects that there is a subset of the scale in which the irregularities are concentrated. Moreover, $D(1)/D(0)$ has also been suggested to indicate heterogeneity of soil particle distribution (Montero 2005), and it can characterize the dispersion of soil PSD. Values of $D(1)/D(0)$ close to 1 will indicate sets with similar dimension, while values close to 0 will be found in distributions with most of the measure concentrated in a small region of the set of sizes (Posadas et al. 2001).

Results can be expressed in terms of the measure's multi-fractal spectrum, $f(\alpha)$, which is defined by a Legendre transformation as follows: