Geoderma 154 (2009) 123–130

Contents lists available at ScienceDirect

Geoderma

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

Fractal features of soil particle-size distribution as affected by plant communities in the forested region of Mountain Yimeng, China

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ARTICLE INFO

Article history:
Received 6 April 2009
Received in revised form 2 October 2009
Accepted 6 October 2009
Available online 30 October 2009

Keywords:
Soil physical properties
Soil particle-size distribution
Fractal dimension
Soil porosity
Plant communities
Yimeng mountainous area

ABSTRACT

Fractal dimension analyses of PSD and soil porosity were determined for the 0–20 cm soil layer representing different plant communities and land management in the Yimeng mountainous region of mid-eastern China. The soil types in this area are typically comprised of coarse sand and gravel. The results show that, compared with the protected forest preserve areas, soil physical properties in commercial Chinese chestnut groves (CM), cropland (ZM) and mixed shrub–grass lands (SH) were more sensitive to soil degradation under their respective long-term management strategies. In general, amounts of silt and clay decreased under CM, ZM, and SH land practices, while fine sand content increased, resulting in lower values for soil total porosity and capillary porosity. For protected forest, soil physical properties were enhanced due to litter decomposition and plant root development under long-term preservation measures. Considering the different plant communities, the overall fractal dimensions of PSD ranged from 2.141 to 2.526, with the fractal dimensions of ZM, SH and CM being far lower (2.141 to 2.166) than the mean value (2.395) of the protected forest land. The relationships between fractal dimension and PSD and soil porosity were also examined. There were significant correlations found between fractal dimension and the amount of silt and clay ($R^2=0.83$), and fine sand ($R^2=0.64$), with increasing fractal dimension values corresponding to higher silt and clay contents and lower sand content. There also existed strong linear relationships between fractal dimension and soil porosity with R^2 values ranging from 0.74 to 0.91. Correlations of D_m with capillary porosity, in association with the type of plant community, provided strong evidence that vegetation management affects small scale aggregation which influences the water-holding capacity of the soil, thus implying that D_m may be considered a good measure for quantifying aggregation and the effects of vegetation management on soil quality or soil degradation. This study demonstrates that fractal dimension analysis may be used to better quantify differences in PSD and soil porosity associated with soil degradation caused by anthropogenic disturbance of plant community environments.

1. Introduction

Fractal theory has been applied to various geological phenomena that display large, scale invariant and self-similar characteristics (Mandelbort, 1982; Katz and Thompson, 1985; Turcotte, 1986). In particular, fractal theory has been shown to be an appropriate means of modeling the process of fragmentation in both rocks and soils as a result of either natural processes or anthropogenic disturbances (Perfect, 1997). Applications of fractal geometry in soil science have shown that soil exhibits fractal characteristics, being a porous medium having different particle compositions, with irregular shape and self-similar structure (Tyler and Wheatcraft, 1989,1992; Rieu and Sposito, 1991a,b; Yang et al., 1993; Kravchenko and Zhang, 1998). Early work by Turcotte (1986) applied the concept of fractals as a means of quantifying the process of fragmentation based on a power law relationship between number of soil grains and grain size. Crawford et al. (1993) evaluated the interpretation of number–size distributions and found that a number–size relation does not necessarily imply fractal structure as assumed. Furthermore, because of the errors introduced by assumptions on grain size and density using the number-based approach, Tyler and Wheatcraft (1992) developed a mass-based distribution to estimate the fractal dimension of the particle-size distribution (PSD). In the work by Tyler and Wheatcraft (1992), they derived fractal scaling relationships for both the solid phase (soil grains) mass and number, and developed the limits of fractal behavior and applications for soil PSDs. Using the mass-based approach, Yang et al. (1993) applied fractal scaling in soil PSDs for different soil textures in the Huabei area of China. Their work demonstrated the effectiveness of using fractal geometry as a descriptive tool in natural porous materials, finding that fractal dimension analysis was very sensitive to clay content.

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doi:10.1016/j.geoderma.2009.10.005

In recent years, the possibility of characterizing particle-size distribution, pore size distribution and aggregate size distribution using fractal theory has been explored by several investigators including Perfect and Kay (1991); Perfect (1997); Kravchenko and Zhang (1998); Bittelli et al. (1999); Millan et al. (2003); Guber et al. (2004); Montero (2005); Filgueira et al. (2006); Miao et al. (2007). Studies such as these and others have shown that fractal theory is a useful tool in quantifying soil structure, soil erodibility, as well as, soil permeability (Rieu and Sposito, 1991a,b; Perfect and Kay, 1995; Huang and Zhan, 2002). In addition, fractal parameters have also become important in understanding and quantifying certain processes associated with soil degradation (Su et al., 2004). There are also a number of studies that apply multifractal analysis of particle-size distributions in soil (Grout et al., 1998; Posadas et al., 2003; Bird et al., 2006; Wang et al., 2008). In an earlier study, Grout et al. (1998) found that a single fractal dimension was insufficient to interpret the complete scale of PSD data on soil grain size distributions obtained from soils comprised predominately of silt and clay. They suggest that, except under very restrictive conditions, PSDs in nature should display multifractal behavior. Wang et al. (2008) used multifractal analysis to characterize PSD and soil quality as influenced by land use in the Loess Plateau of China. In this area of highly erosive soils, of rather homogeneous silt loam texture, they found that selected multifractal parameters were significantly correlated with finer particle content and soil organic matter.

Changes in land management practices may affect soil structure in ways that diminish the overall soil quality (Filgueira et al., 1999; Islam and Weil, 2000; Wang et al., 2006). For example, the removal of native vegetation from an area with a high soil erosion potential could result in the selective removal of fine particle-size fractions caused by overland flow during the soil erosion process. Thus, different types of land-use and vegetation types largely influence PSD by either enhancing or inhibiting soil erosion (Martínez-Casasnovas and Sánchez-Bosch, 2000; Erskine et al., 2002; Basic et al., 2004; Fullen et al., 2006; Wang et al., 2008). Wang et al. (2008) conducted a study to determine the effect of land-use types on multifractal parameters of PSD in the Loess Plateau of China. They found that for 70 soil PSDs, multifractal parameters could potentially serve as indicators to reflect soil properties and soil quality influenced by land use. In the arid and semi-arid regions of the Tibetan Plateau in China, Wang et al. (2006) determined the fractal characteristics of soils under different land-use patterns. The results of their study show that land use had a considerable effect on the fractal dimension of PSD and other soil properties. Thus, fractal dimensions of PSD may be a useful parameter for determining the influence of land-use and plant communities on soil properties, as well as a means to monitor soil degradation induced by changes in land use.

Over the course of the past few decades, much of the Yimeng mountain forest in mid-eastern China has been destroyed due to economic growth and the exploitation of natural resources. Some plant communities have been transformed from protected forest areas to commercial forest (chestnut groves), cropland, or shrub–grassland areas for grazing. While many studies have focused on the fractal behavior in PSD analyses, few studies have applied fractal theory to determine the influence of different plant communities or land management on PSDs for similar soils. Furthermore, to date, no studies have been published investigating the soil fractal features associated with different plant communities in the Yimeng mountainous area. In this paper, we use the fractal scaling theory of Tyler and Wheatcraft (1992) to analyze PSD, soil porosity and soil fractal dimension for seven different plant communities having similar soil types and evaluate the relationships between selected soil properties and the fractal dimension of PSD. The objectives of this work were: 1) to assess the effect of converting native forests to different land uses on soil physical properties and, 2) to explore the possibility that the fractal dimension of soil particle-size distribution can be used as an integrating index for quantifying soil degradation due to anthropogenic disturbance.

2. Materials and methods

2.1. Soil fractal model theory

The definition of a fractal can be given based on the relationship between number and size in a statistically self-similar system and defined by the following equation (Mandelbort, 1982; Turcotte, 1986):

$$N(X>x_i) = kx_i^{-D} \quad (1)$$

where $N(X \geq x_i)$ is the cumulative number of objects or fragments greater than a characteristic size, x_i, k is the number of elements at a unit length scale, and D is the fractal dimension. However, the applicability of Eq. (1) in PSD analysis is limited because complete and accurate calculations of N values are typically not available from conventional PSD experimental data.

In an effort to compensate for the lack of N values, Tyler and Wheatcraft (1992) estimated the fractal dimension of soil particle-size distribution, D_m, based on the following expression:

$$M(r<R_i)/M_T = (R_i/R_{max})^{3-D}_m \quad (2)$$

where M is the cumulative mass of particles of ith size r less than R_i, M_T is the total mass, R_i is the mean particle diameter (mm) of the ith size class, and R_{max} is the mean diameter of the largest particle, respectively. The mean particle diameter is taken as the arithmetic mean of the upper and lower sieve sizes. We employ the use of Eq. (2) in the analysis of this study.

2.2. Study area description

The study was conducted at the Tashan forestry farm of Fei county, located in the hinterland of the Yimeng mountain area, Shandong province, mid-eastern China (Fig. 1). The geographical coordinates are, 35° 25′ 10″ to 35° 30′ 4″ N and 117° 59′ 15″ to 118° 4′ 37″ E. It has a continental warm temperate monsoon climate. The average annual temperature is 13.6 °C. The average annual evaporation is 858 mm with 65% occurring between May and June. The average annual precipitation is 819 mm with 75% occurring between June and September. The topography of this area is characterized by low mountains and hills (accounting for 76.6% of total area). The altitude above sea level is between 200 m and 800 m. The soil types in this area are typical of skeletal soils (predominately sand and gravel) commonly found in mountainous areas. The parent rock material is granite-gneiss and limestone. The zone vegetation type of this area is warm temperate deciduous broad-leaves. Common types of arboreal vegetation in the area include *Pinus densiflora*, *Quercus acutissima*, *Robinia pseudoacacia*, *Platycladus orientalis*, *Castanea mollissima* and *Crataegus pinnatifida*. Herbage and shrub vegetation mainly include *Lespedeza bicolor*, *Vitex negundo heterophylla*, *Poa annua*, *Roegneria kamoji*, *Artemisia argyi* and *Rubus parvifolius.*

2.3. Plant community investigation

Seven typical plant communities were selected within the study area according to the four types of land use (Table 1). Plant communities were defined as, *P. densiflora pure forest* (PD), *Q. acutissima pure forest* (QA), *R. pseudoacacia pure forest* (RP), *P. densiflora* and *Q. acutissima mixed forest* (PQ), *C. mollissima forest* (CM), *Zea mays crop* (ZM) *and Scrub and herbose* (SH). According to land-use type, the former four plant communities (PD, QA, RP and PQ) are within protected forestland preserve areas, CM is in Chinese chestnut