Geoderma 328 (2018) 91–99

Contents lists available at ScienceDirect

Geoderma

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

Geostatistical analysis of pedodiversity in Taihang Mountain region in North China

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ARTICLE INFO

Handling editor: A.B. McBratney

Keywords:
Soil diversity
Semivariance
Land use
Population density
Protection zone

ABSTRACT

The protection of pedodiversity is very important for biodiversity maintenance and food production. However, where and how large should the protection focus on in a given region (especially in mountain regions with complex environment) remains unclear. In this study, geostatistical analysis was used to study pedodiversity indexes (Shannon's index, the maximum Shannon's index, Richness index and Evenness index) in Taihang Mountain region in North China. Then pedodiversity protection and buffer zones were designed. Moreover, the relationship between protection zone and human activities was determined. The results showed that average Shannon's index for the study area was 1.72, with two lower value zones appeared in the north and the south of Taihang Mountain region, respectively. This suggested that there was the need to enhance the protection of pedodiversity in the two regions. The ranges of the Richness index and the Shannon's index were respectively 57.16 km and 96.00 km, indicating that pedodiversity had spatial dependence within these distances. Therefore, protection zones with radius of 57.16 km and buffer zones with radius of 96 km was designed. For both the northern and southern protection zones, the percent area of population density lower than 1 person/km^2 (35.27% for the north and 51.71% for the south) was much higher than the average value (27.91%) of Taihang Mountain region. Furthermore, the percent area of farmland (43.72% for the north and 40.48% for the south) were higher than the average value (35.92%). This demonstrated that human activity, especially farming, was a key consideration in the protection of pedodiversity in the study region. The results of the study constitute a significant contribution to the theory of pedodiversity protection and soil resources management.

1. Introduction

Pedodiversity, also known as soil diversity, is the basis for biodiversity. In spite of the increasing interest in recent years, the study of pedodiversity lags far behind that of biodiversity (Guo et al., 2003; Minasny et al., 2010; Fajardo et al., 2017; Fu et al., 2018). The concept of pedodiversity was originally proposed in the 1990s (Mcbratney, 1992; Ibañez et al., 1995). Since then, it has gradually attracted global scientific attention and focus (Amundson et al., 2003; Toomanian et al., 2006; Shangguan et al., 2014). Pedodiversity study reached a peak level in the 2010s, with the publication of the book *Pedodiversity* in Springer (Ibáñez and Bockheim, 2013) and the follow-up special issue in *Geomorphology* (Volume 135, Issues 3–4). Irrespectively, the study of pedodiversity still remains much weaker than that of biodiversity. This underscores the need for more studies on pedodiversity.

Existing studies on pedodiversity have focused mainly on four areas. First, pedodiversity index; which come from the methods used to study biodiversity. This mainly includes the Shannon's index, Richness index, Evenness index and their derivatives (Ibañez et al., 1995; Tan et al., 2003; Danek et al., 2016). Second, object abundance models; which describe the distribution of objects abundance (Ibañez et al., 1998; Toomanian et al., 2006; Kooch et al., 2015). Four main types of models always used for this purpose include geometric model, logarithmic model, logarithmic normal model and broken stick model (Ibañez et al., 1995). Each of these models is related to a distribution pattern of soil individuals. Third, pedodiversity-area or richness-area relationship; which relationship is given by power or logarithmic function (Guo et al., 2003; Ibáñez et al., 2005; Ren and Zhang, 2015). Pedodiversity-area relationship is closely related to the object abundance models, with the power curve accompanied by lognormal and broken-stick models, and the logarithmic expressions by geometric and logarithmic series models (Saldaña and Ibáñez, 2007). Fourth, rare and endangered

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https://doi.org/10.1016/j.geoderma.2018.05.010
Received 26 November 2017; Received in revised form 28 March 2018; Accepted 6 May 2018
0016-7061/

soils studies; which is mainly about soils that are significantly influenced by humans (Amundson et al., 2003; Shangguan et al., 2014; Tennesen, 2014). In summary, most of the existing studies on pedodiversity are concerned mainly with basic theories of pedodiversity. Only the studies of endangered soils provide information on soil protection. With the existing soil databases, land planning can be used to protect pedodiversity and cultural heritage (Costantini et al., 2007; Ibáñez et al., 2008). However, exactly where and to what extent is considered appropriate for sustainable protection remain largely unclear.

Geostatistics, which is based on the theory of regionalized variables, is a branch of applied statistics that focuses on the detection, modeling and estimation of spatial patterns (Rossi et al., 1992; Goovaerts, 2000; Webster and Oliver, 2007). The most used methods in geostatistical analysis are semivariogram and kriging. From semivariogram, nugget (C_0), sill ($C_0 + C$), range and other parameters can be derived. The nugget-to-sill ratio ($C_0/(C_0 + C)$) reflects the degree of spatial dependence. Based on Cambardella et al. (1994), spatial dependence is strong when $C_0/(C_0 + C)$ ratio $< 25\%$, moderate when between 25 and 75% and weak when $> 75\%$. The range reflects the correlation length beyond which the sampling points are independent. Because of the ease and practicability of geostatistical method, it is widely used in the study of soil moisture, soil nutrient, soil texture and other soil property analysis (Duffera et al., 2007; Bourennane et al., 2014; Fu et al., 2016; Bogunovic et al., 2017), as well as the study of biodiversity (Gholami et al., 2017; Liparoto et al., 2017). Nevertheless, geostatistics is hardly tried in the study of pedodiversity. The use of geostatistics in pedodiversity can be useful in understanding the spatial structures of pedodiversity and can provide meaningful information on pedodiversity protection zones.

The study of pedodiversity began in China in 2001 (Chen et al., 2001). Since then, it has gradually intensified in Shandong Province, Nanjing City, Henan Province and other areas in the country (Tan et al., 2003; Zhang et al., 2007; Ren and Zhang, 2017). Besides regional studies, there also are studies which focus on the whole China (Zhang and Gong, 2004; Shangguan et al., 2014). However, mountain areas, which have complex environmental conditions, are largely ignored in these studies. Taihang Mountain, which is in North China, is an important boundary region between the Loess Plateau and the North China Plain (NCP). The special location of Taihang Mountain makes it an important ecological area (Yang et al., 2003). However, this mountain region is threatened by serious ecological degradation, including soil depletion, natural hazards, overgrazing, etc. (Li et al., 2004). The loss of pedodiversity is also a very serious problem in Taihang Mountain. There are more rare-unique soils and endangered soils in this mountain area than in other areas of China (Shangguan et al., 2014); requiring considerable attention for pedodiversity assessment, protection and sustainability.

The objectives of this paper were to: (1) obtain the geostatistical characteristics of pedodiversity indexes, (2) determine protection zones and buffer zones, and (3) analyze the relationship between protection zones and human activities in the Taihang Mountain area, north China.

2. Materials and methods

2.1. Site description

Taihang Mountain is located in North China, extending in the southwest-northeast direction (Fig. 1). Taihang Mountain region extents across a total of 4 provinces (Beijing, Hebei, Shanxi and Henan) and 101 counties. It is an important transition zone between the Loess Plateau and NCP. Because of its special location and orogeny, the western and eastern parts of Taihang Mountain are very different in structural evolutions, sedimentation processes and tectonic settings (Wang and Li, 2008).

Taihang Mountain is influenced by the East Asian Monsoon climate. The summer is warm and rainy, and the winter is cold and dry. Based on 10-year (2005–2014) meteorological data in the region, average annual temperature is 11.4 °C, with the highest in July and lowest in January. The average annual precipitation is 457 mm, with the highest in July and lowest in December. Average elevation range is 1000–1500 m, with the northwest higher than the southeast. The slopes are generally steep and often over 25°. The main land use types include farmland (35.92%), forestland (29.05%), grassland (26.44%) and others (8.59%). The vegetation is influenced by the elevation, slope gradient, slope aspect and the interaction effects of these factors (Zhang et al., 2006). Soils are always thin in Taihang Mountain, with an average thickness of 35 cm (Cao, 2011). The soils are mainly developed from limestone in the northern and southern regions, but from gneiss in the central region. Based on the first-level FAO soil classification (Harmonized World Soil Database), 26 soil types exist in Taihang Mountain. The most common are Cambisols and the most uncommon are Podzoluvisols. Detailed information on soil types is given by Fu et al. (2018).

2.2. Pedodiversity indexes

Richness index (S) defines the number of soil types within a given region, which can be a country, a catchment or even a regular grid of in the area.

Another important pedodiversity index is the Shannon's index. It is based on proportional abundance of objects and it is expressed as:

$$\mathrm{H} = -\sum_{i=1}^{i=n} p_i \times \ln p_i \tag{1}$$

where p_i is the proportion of individual number of the i^{th} object (area of i^{th} soil type) to the total number of individuals (total area of the given region). The value H varies between 1.5 and 3.5 and rarely exceeds 4.5 (Margalef, 1972). When all the objects (soil types) are evenly distributed, the Shannon's index is then maximum and is expressed as:

$$H_{max} = \ln S \tag{2}$$

Actually, the Shannon's index rarely reaches its maximum value and the proportion of H to H_{max} is the evenness index (E), expressed as:

$$\mathrm{E} = \frac{H}{H_{max}} \tag{3}$$

The range of E is 0–1 and higher E values means more even distribution of soil types.

2.3. Geostatistical analysis

Semivariance and spatial interpolation (Kriging interpolation) are the two wildly used methods in geostatistical analysis. The semivariance ($\gamma(h)$) of a regionalized variable is expressed as (Webster and Oliver, 2007; Fu et al., 2015):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \tag{4}$$

In the formula, $N(h)$ is the paired points at lag distance h; $Z(i)$ is the value of the variable at point x_i; and $Z(x_i + h)$ is the value at a point which is h meters away from point x_i.

The relationship between semivariance and lag distance is always simulated by Spherical model, Exponential model or Gaussian model as:

$$\gamma(h) = \begin{cases} C_0 + C\left(\frac{3h}{2a} - \frac{h^3}{a^3}\right) & 0 \le h \le a \\ C_0 + C & h \ge a \end{cases} \tag{5}$$

$$\gamma(h) = C_0 + C\left(1 - e^{-\frac{h}{a}}\right) \tag{6}$$

$$\gamma(h) = C_0 + C\left(1 - e^{-\frac{h^2}{a^2}}\right) \tag{7}$$