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Spatial analysis of soil aggregate stability in a small catchment of the Loess Plateau, China: I. Spatial variability

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A B S T R A C T

The intrinsic and extrinsic factors that control soil aggregate formation have been widely studied at the aggregate scale, but little is known about their roles in aggregate formation at different landscape scales. Here, a spatial analysis of soil aggregate stability and erodibility (K factors) was performed to understand the formation processes of aggregates at catchment scale. Spatial structures of the mean weight-diameter (MWD, mm), water-stable aggregates greater than 0.25 mm ($WSA_{>0.25}$, %) and K factors were investigated by using classical statistics, semivariograms, Local Indicators of Spatial Association (LISA), spatial interpretation, and spatial overlay in a small catchment of the Loess Plateau, China (LPC). The results showed that MWD and $WSA_{>0.25}$ were significantly lower in farmland than in other land types, and were obviously higher in shrubland than in woodland, but it was the opposite case for K factors. Nugget/sill ratios $C_0/(C_0 + C)$ showed a very strong spatial dependence for MWD (9.13% at 0–10 cm and 19.49% at 10–20 cm soil layer) and $WSA_{>0.25}$ (12.48% at 0–10 cm and 17.71% at 10–20 cm soil layer). These data and LISA results implied that the spatial variability of MWD, $WSA_{>0.25}$ and K factors in the Zhifanggou catchment was mainly controlled by intrinsic factors such as parent materials, terrain attributes and soil types. Besides, the effects of extrinsic factors (land use and farming practice) could not be ignored, especially for K factors. Cross-validation results illustrated that ordinary kriging (OK) performed better than inverse distance weighting (IDW) for MWD and $WSA_{>0.25}$, but it was the opposite for K factors as a whole. Land-use type, topography, vegetation, and revegetation duration showed interactive effects on the spatial heterogeneity of soil aggregate stability and K factors. Spatial analysis showed great potential to be applied in the analysis of the influencing factors of soil aggregate stability at the small catchment scale.

1. Introduction

Soil aggregates are the basic units of soil structure, and their stability is critical for soil water movement and storage, fertility, aeration, erosion, carbon sequestration, biological activity, and root penetration (Algayer et al., 2014a; Amezketa, 1999; Gallardo-Carrera et al., 2007; Deng et al., 2014; Jastrow and Miller, 1997; Lynch and Bragg, 1985; O'Brien and Jastrow, 2013). Soil aggregate stability and erodibility K factors are often used as the key indices to evaluate soil degradation or soil erodibility (Algayer et al., 2014b; Shi et al., 2012). The large spatial variability of aggregate stability and K factors is inherent because of geologic and pedologic soil forming factors, and a part of this variability may result from agricultural management or human disturbance. Therefore, digital mapping of soil aggregate stability and K factors is significant for the evaluation of soil erosion, and analysis of their spatial heterogeneity may facilitate a understanding of the aggregate formation processes and the reasons for their spatial differences (Cambardella et al., 1994; Castrignanò et al., 2000).

Classical statistics (Cantón et al., 2009; Hajabbasi and Hemmat, 2000) and geostatistics (Cambardella et al., 1994; Castrignanò et al., 2000) are generally used to study the spatial heterogeneity of aggregate stability and soil erodibility. Classical statistics requires some basic hypotheses, such as the spatial independence of variables, which may produce erroneous or misleading results (Nielsen and Alemi, 1989). Conversely, geostatistics was established based on the theory of regionalized variables, considering the spatial dependence of variables. It enables the

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analysis, assessment and interpretation of the spatial structures of regional variables, and the prediction of variables at unknown locations.

In recent years, more and more studies of spatial variability in soil properties have been performed by geostatistics (Cambardella et al., 1994; Freitas et al., 2015; Júnior et al., 2006; Ou et al., 2017). However, research on the spatial patterns of aggregate stability is limited (Castrignanò et al., 2000; Castrignanò and Stelluti, 1999; Shukla et al., 2007; Siqueira et al., 2010) compared with that on other soil properties, such as soil texture (Langella et al., 2016; Wang and Shi, 2017), soil moisture (Júnior et al., 2006) and soil organic carbon content (SOC) (Annabi et al., 2017). Cambardella et al. (1994) analyzed the spatial distributions of different soil variables at two sites within a catchment in central Iowa and suggested that spatial relationships were comparable within the similar landscapes. Barik et al. (2014) determined the effects of traffic compaction on the changes in spatial variability of soil properties and showed that aggregate stability is significantly affected by traffic operation. Current literatures about the spatial variability of aggregate stability ignore the local spatial autocorrelation and the local clusters of similar behavior in the spatial arrangement. Besides, these studies have confirmed the important effects of environmental factors such as topography, land use and vegetation on the heterogeneity of aggregate stability and soil erodibility at different spatial scales. However, their interactive effects remain unclear.

The Loess Plateau of China (LPC) covers an area of 640,000 km^2 in northwestern China, and is recognized as the most eroded landscapes in the world. The soil of LPC was developed from loess deposits (Wang et al., 2017). A unique combination of climate, topography, vegetation factor, soil property, and unsustainable agricultural practices leads to severe soil erosion (Zhang, 1991). The severe soil erosion can be effectively prevented by afforestation, but it is still severe in cultivated slope farmland (Zhang et al., 2008). Then the "Grain for Green" project (GGP) was implemented in 1999 to restore the fragile ecosystems by converting the slope farmland and wasteland into grassland, shrubland and woodland (Zhou et al., 2012). The significant achievements of GGP in controlling soil erosion have been widely acknowledged. However, little is known about the spatial distribution of soil erosion resistance on LPC. Hence, it is necessary to understand the spatial variability and spatial autocorrelation of aggregate stability and soil erodibility on LPC. The Zhifanggou catchment, which is located at the center of LPC, is a typical hilly gullied loess landscape, and its soil was derived from wind-accumulated loess parent material and has a vertically and laterally uniform silt loam texture. After 30 years of ecological restoration supported by the Chinese Academy of Sciences, the Zhifanggou catchment has become a popular catchment for understanding the soil and water conservation on LPC (Wang et al., 2011; Zhao et al., 2017; Zhao et al., 2016; Zhou et al., 2006). Several practical revegetation methods have been applied at different times since the 1980s, making the Zhifanggou catchment an appropriate environment for studying the intrinsic and extrinsic factors that control the soil aggregate formation. In addition, abundant basic data about Zhifanggou catchment are available, providing an excellent data platform for furture research such as the National Earth System Science Data Sharing Infrastructure, http://loess.geodata.cn.

The present study was aimed to (1) analyze the variation of aggregate stability and soil erodibility under different land-use types and identify the reasons based on the aggregate size distribution by classical statistics, (2) evaluate how spatial variability of aggregate stability and K factors are affected by land-use types, vegetation, topography, and revegetation at the local spatial scale, and (3) how these factors determine their spatial distributions by semivariograms, Local Indicators of Spatial Association (LISA), and spatial interpretation.

2. Materials and methods

2.1. Study area and soil sampling

Zhifanggou catchment is located at the Ansai Research Station of Soil and Water Conservation in Shaanxi Province in the center of LPC. It is a typical catchment in the hilly gullied loess landscape with slopes varying from 0° to 65° (109°13′03″ – 109°16′46″ E longitude, 36°46′28″ – 36°46′42″ N latitude, 1010 – 1431 m altitude, 8.27 km^2) (Fig. 1a, b). The climate is typically semiarid with a mean annual temperature of 8.8 °C (−23.6 °C to 36.8 °C). Its average annual precipitation is about 505 mm and falls between July and September with over 60% precipitation. The soil is mainly Orthic Entisol according to Chinese Soil Taxonomy (Cooperative Research Group on Chinese Soil Taxonomy (CRGCST, 2001) or Calcaric Regosols according to WRB reference system (IUSS Working Group WRB, 2014), and was derived from wind-accumulated loess parent material with an average thickness of 50–80 m. The soil is of a uniform silt loam texture, and the average sand, silt and clay contents are 21 ± 6%, 63 ± 3%, and 16 ± 4%, respectively (Fig. S1). The average soil pH (1:2.5 soil: water) is 8.02–8.63 (Fig. S2). The main land-use types include farmland (*Zea mays L.*; *Panicum miliaceum L.*; *Malus pumila*; *Armeniaca vulgaris Lam.*), woodland (*Robinia pseudoacacia L.*; *Pinus tabuliformis Carrière*), shrubland (*Caragana korshinskii*; *Hippophae rhamnoides L.*), and grassland (*Agropyron cristatum*; *Lespedeza davurica*; *Artemisia sacrorum*; *Caragana microphylla*; *Stipa bungeana*; *Artemisia giraldii Pamp.*; *Stipa grandis*; *Heteropappus altaicus*). *Stipa bungeana* is the most widely distributed vegetation.

A stratified random sampling irregular grid was designed by taking into account, terrain condition (Fig. 1b), land-use type (Fig. 1c), and accessibility. The land use map was obtained by vectorizing the aerial photo with 40 cm resolution (available at http://loess.geodata.cn) developed by the Loess Plateau Data Center, National Earth System Science Data Sharing Infrastructure. As for the sampling process, a 300 × 300 m grid was designed for field sampling first. The locations of sampling site were determined to cover as many landscape units of different landforms, terrains, land use types, and vegetation factors as possible. In addition, some sampling sites such as cliffs and deep gullies were not accessible. As a result, an irregular grid was obtained. A global positioning system (GPS) receiver was used to identify the positions of sampling points and a photo camera was used to record the whole sampling process. Field management data were obtained at the site by field observation and farmer interviews. To compare the differences in soil structure distribution and the effects of environmental factors on soil structure at different soil layers, 70 sampling sites (Fig. 1b) were selected to represent the major landscape units at 0–10 cm and 10–20 cm soil layers with three replicates from the same location during June 19th to 26th, 2016. Aluminum containers were used to collect undisturbed soil samples for avoiding soil structural deformation or destruction (Fig. 1d). The soil samples were air-dried afterwards.

2.2. Measurement of aggregate stability

The aggregate stability was measured by using the wet sieving method (Kemper and Rosenau, 1986). Approximately 300 g of air-dried soil samples were sieved on a sieve shaker using a column of sieves at mesh sizes of 5, 2, 1, 0.5 and 0.25 mm. The weights of aggregates remaining on the sieves were recorded and their percentages in the bulk soil were calculated. 50 g of air-dry soil aggregates were prepared based on the above-mentioned percentages. Then, the composed soil samples were sieved for 1 min (30 times) in water (3 replicates). The aggregates with diameters > 5 mm, 5–2 mm, 2–1 mm, 1–0.5 mm and 0.5–0.25 mm were separated again. Then, aggregates remaining on the sieves were transferred into clean beakers. These beakers with soil materials were oven-dried and weighed. Soil aggregate stability was expressed by the mean weight diameter (MWD, mm), percentage of water-stable aggregates that were greater than 0.25 mm ($WSA_{>0.25}$, %), and geometric mean diameter (GMD) by wet sieving. Then, the soil erodibility factors (K factors) were calculated based on the GMD (Li et al., 2016). Equations used in this research include: