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Spatial distribution of caliche nodules in surface soil and their influencing factors in the Liudaogou catchment of the northern Loess Plateau, China

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ABSTRACT

Quantifying the distribution of caliche nodules in a catchment is a basis toward understanding soil erosion and soil degradation as well as soil-water processes in the soil containing caliche nodules. In this study, field surveys and soil sampling were coupled with spatial and statistical analyses along with image processing to investigate the spatial distribution of caliche nodules and their influencing factors in the Liudaogou catchment, the northern Loess Plateau of China. Results showed that more caliche nodules were present at the top of the mountain, mountain ridges, roadsides, edges of ravines, and other high elevation regions, as represented by comparatively higher caliche nodule coverage (CNC, 11.26–18.28%). Caliche nodules were rarely present in low elevation areas such as the terraced cropland and check dam, as represented by lower CNC ($< 2.55\%$). More than 65% of the total caliche nodules had a diameter of 10–50 mm. The caliche nodule coverage and diameter showed strong spatial dependence. The CNC was significantly related to the slope gradient and vegetation cover ($P < 0.01$), and the caliche nodule diameter (CND) was significantly related to the elevation ($P < 0.01$). Two simple models were established to predict the CNC and CND values given the parameters of slope gradient and vegetation cover. The validation of the models showed relatively high accuracy. These findings quantify caliche nodule distribution in a catchment for the first time, and may benefit the assessment of soil erosion and soil degradation in this special soil in the Loess Plateau.

1. Introduction

Soil degradation is a significant environmental problem (Arbelo et al., 2006; McHunu and Chaplot, 2012; Seeger and Ries, 2008; van den Akker, 2010). A sign of soil degradation is the presence of large particles (diameter > 2 mm) such as rock fragments, caliche nodules, pebbles, gravels, and small stones in surface soil which occur as a result of soil erosion and human activities (Chen et al., 2011; Poesen and Lavee, 1994; Zhu and Shao, 2008). Soils containing large particles are widely distributed in mountainous areas, river basins, and areas with sedimentary soils and high rates of calcium leaching like the Loess Plateau of China (Chen et al., 2011; Gong and Zhu, 2016; Poesen and Lavee, 1994; Poesen et al., 1998; Zhang et al., 2016; Zhu and Shao, 2008). The large particles indicative of these areas is different from a soil particle in size and physical and chemical properties. Their presence can change soil-water processes and influence the water cycle and vegetation growth. It is necessary to investigate this kind of soil to improve management of soil and water resources.

The large particle can be classified into two groups based on its genesis. The first class is the large particle as an external material invading into the soil. This kind large particle includes rock fragments, pebbles, flint stones and chalk, and sedimentary fragments. The second class is the large particle as a product of calcium leaching generated in the process of soil genesis such as a caliche nodule, which is commonly present in areas rich in soil calcium. Due to the wide distribution of soils containing large particles, many studies have been conducted with these soils in recent decades. These studies have found that large particles can change soil pore structure and affect soil water content (Danalatos et al., 1995) and hydrological processes such as evaporation (Cousin et al., 2003; Govers et al., 2006; Kemper et al., 1994; Lv et al., 2000; van Wesemael et al., 1996), infiltration (Brakensiek and Rawls, 1994; Ravina and Magier, 1984; Valentin, 1994; Valentin and Casenave, 1992; Verbist et al., 2009), and water movement (Cousin et al., 2003; Hlaváčiková et al., 2015; Ma et al., 2009, 2010; Novák et al., 2011; Sauer and Logsdon, 2002). Large particles can also change slope runoff and sediment yield by preventing soil sealing and

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increasing water infiltration (Poesen and Lavee, 1994), and the magnitude of the effect depending on their size and position in the soil (Valentin, 1994; Valentin and Casenave, 1992; van Wesemael et al., 1996; Verbist et al., 2009). As a result, many equations have been developed in efforts to predict physical and hydraulic properties in this kind soil (Hlaváčiková and Novák, 2014; Ma et al., 2009, 2010; Novák et al., 2011; Sauer and Logsdon, 2002).

Quantifying the spatial distribution of large particles is required to advance our understanding of the spatial variability of erosion. Previous studies have reported that the distribution pattern of large particles on a hillslope is reflective of land use, slope gradient, topography, and vegetation (Chen et al., 2011; Gong and Zhu, 2016; Li et al., 2007; Poesen et al., 1998; Simanton et al., 1994; Zhu and Shao, 2008). Most previous studies found a positive relationship between slope gradient and rock fragment cover or size (Simanton et al., 1994; Simanton and Toy, 1994; Zhu and Shao, 2008; Li et al., 2007; Poesen et al., 1998). However, some studies reported a logarithmic increase in rock fragment cover with increased slope gradient in the southeastern semiarid rangelands of Arizona, USA (Simanton and Toy, 1994; Simanton et al., 1994). As for the factors controlling the distribution of large particle, slope gradient and morphology are dominant (Poesen et al., 1998). The lithology of the large particle, land use, and vegetation can also change rock fragment distribution along a slope (Chen et al., 2011; Govers et al., 2006; Nyssen et al., 2002; Zhu and Shao, 2008). However, most of the past research on the distribution of large particles has been conducted at a slope scale (Chen et al., 2011; Govers et al., 2006; Li et al., 2007; Nyssen et al., 2006; Poesen et al., 1998; Simanton and Toy, 1994; Simanton et al., 1994; Zhu and Shao, 2008). A slope is only the basic unit comprising a watershed. Quantifying its distribution in the watershed is not only progressive over the current slope scale, but also can provide basic data for soil-water processes modeling. A majority of past work has focused on the first class of large particles (external material invading the soil, i.e., rock fragments, pebbles, etc.) with less work on caliche nodules, a common large particle in the northern Loess Plateau of China. Due to severe soil erosion, caliche nodules are increasingly present in the surface soil in this region, and therefore their role in soil-water processes must be explored. Quantifying caliche nodule distribution and its influencing factors at a catchment scale is important not only due to the reasons mentioned above but also to acquire a better understanding of the relationships between caliche nodules and environmental factors, which is crucial for management of soil and water resources as well as for the sustainable revegetation in the northern Loess Plateau.

The aims of this study were to: 1) obtain the spatial distribution pattern of caliche nodules in the Liudaogou catchment, the northern Loess Plateau of China, 2) analyze the relationships between the caliche nodules and environmental factors, and 3) establish models to predict caliche nodule distribution.

2. Materials and methods

2.1. Study area

This study was conducted in the Liudaogou catchment (E110°21′–110°23′ N38°46′–38°51′), Shenmu county, Shaanxi Province of China (Fig. 1). The catchment is located in the wind-water erosion crisscross region of the Loess Plateau. The altitude and area of the catchment are 1081–1274 m above sea level and 6.89 km^2, respectively. The mean annual temperature and precipitation for the catchment are 8.4 °C and 408 mm, respectively; 81% of the total precipitation falls between June and October. The local soil is classified as aeolian loess. Soil erosion modulus in the catchment is 15,040 $t \cdot km^{-2} \cdot a^{-1}$, and soil and water loss areas account for 79% of the total area. The landform of the catchment is highly fractured with a gully (> 100 m) density of 6.45 $km \cdot km^{-2}$, and the proportion of the gully area to the total is around 38%. The dominant vegetation in the catchment is drought shrub–clustered grassland (*Caragana korshinskii* and *Stipa capillata* Linn). In the catchment, the caliche nodules are a product of high calcium soil subjected to alternate drought-wet climate conditions, and they are frequently found in topsoil due to intensive soil erosion. The mass percentage of calcic nodules in the soil reaches 5–30% (Gong and Zhu, 2016; Zhu and Shao, 2008).

2.2. Soil sampling and image acquirement

A traditional grid method was used to obtain sampling sites using ArcMap (version 10.2) within the catchment. Each grid represented an area of 350 m × 350 m. Because the caliche nodules are not ubiquitously distributed, parts of grid sampling sites were excluded due to the absence of caliche nodules. Consequently, we used the grid sampling method only in the areas that were rich in caliche nodules; 61 sites were selected for soil sampling (Fig. 1). Of these sites, 28 sites contained caliche nodules and the remaining were in the homogenous soil (without caliche nodules). Within each of the 28 sites, a 1 m × 1 m sampling frame was put on the soil surface and an orthographical image of the site was taken by a digital camera (Sony DSC hx1, its specifications see Table 1). As for the sites in the soil without caliche nodules, only orthographical images were taken. At the same time, environmental elements (including geographic coordinates, slope gradient, slope position, elevation, and land use) and vegetation elements (i.e., vegetation cover, height, and number of species) were recorded, respectively. Then, the caliche nodule index, which is determined by the caliche nodule coverage and diameter, were determined by image processing in software Image-Pro Plus 6.0 (Media Cybernetics, Inc., USA).

2.3. Image processing

After acquiring an image of each site, ROI (region of interest) was extracted and cropped into a standard size of 1 m × 1 m. As for the 28 sites containing caliche nodules mentioned above, ROI was the image inside the sampling frame. The ROI image had a projection correction applied using Photoshop 15.0 and then was processed using software Image-Pro Plus 6.0. The procedure of image processing (1 → 2 → 3 → 4) is shown in Fig. 1b (Zhu and Shao, 2008).

2.4. Data analysis

2.4.1. Parameters calculation

Because caliche nodules are not a perfect sphere, we use an equivalent diameter to represent their size. The equivalent diameter of a caliche nodule (D_{CN}) is calculated as:

$$D_{CN} = 2 \times \sqrt[2]{\frac{A}{\pi}}$$

where, A is the area of caliche nodule in the image (cm^2).

The Species richness (R), Shannon-Wiener diversity index (H) and Evenness index (E) of the grassland communities were calculated using the following functions:

$$\text{Species richness:} \mathrm{R} = \mathrm{S}$$

$$\text{Shannon} - \text{Wiener diversity index: } \mathrm{H} = -\sum_{i}^{s} (P_i \ln P_i)$$

$$\text{Evenness index:} \mathrm{E} = \frac{H}{\ln S}$$

where, S is the total number of species in the grassland community, P_i is the density of the i^{th} species and H is the Shannon-Wiener diversity index.