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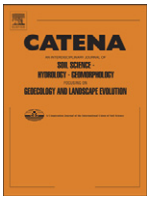

Spatial distribution of biological soil crusts on the slope of the Chinese Loess Plateau based on canonical correspondence analysis

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ABSTRACT

Biological soil crusts (BSCs) are a living ground cover widely distributed in arid and semi-arid regions, and providing important ecological functions in arid and semi-arid ecosystems. An understanding of the spatial distribution patterns of BSCs is foundational for the scientific management of this resource. In this study, a typical slope was selected from a small watershed, Liudaogou, in the wind–water erosion crisscross region of the Loess Plateau in northwest China. The spatial distribution characteristics of BSCs and associated influencing factors were investigated at the slope scale via a comprehensive survey and statistical analysis using GS+ and CANOCO statistical software. The results showed that the distribution of BSCs was clearly spatially differentiated, with the majority of BSCs widely and continuously distributed in sandy areas at a mean coverage of greater than 30%. Sporadic distribution of BSCs was observed in loess areas mainly at the edges of slopes with a mean coverage of generally less than 20%. The thickness and shear strength of the BSCs did not present significant spatial variation, indicating that these two BSC indices were primarily associated with the age and developmental stage of the BSC which was relatively constant throughout the study area. A canonical correspondence analysis revealed that the spatial distribution of BSCs was closely correlated with soil type, vegetation, surface soil moisture content, slope and aspect. Among these factors, soil type had the most significant impact on BSC distribution and explained 20% of the spatial variation of BSCs. The vegetation community type and topographic wetness index were the secondary influencing factors, and sagebrush (*Artemisia desertorum*) shrubland and aspen (*Populus simonii*) woodland provided the most ideal growth environments for BSCs. Other factors such as slope, aspect and solar radiation also affected BSC distribution to a certain degree. Overall, BSCs were clearly selective for topography, soil type and vegetation community and preferentially grew in humid areas with psammophytic plant communities.

1. Introduction

Biological soil crusts (BSCs) are complex aggregations of soil particles cemented together by microorganisms, algae, lichens, mosses and other living organisms as well as their metabolites. BSCs form a ground cover and are frequently found in arid and semiarid regions (Belnap, 2003), where they have important ecological functions (Bowker et al., 2010; Bu et al., 2015a; Viles, 2008; Yu et al., 2012;) and positively affect soil and water conservation (Bu et al., 2015b). The ecological functions of BSCs and their potential effects on desertification are also attracting more attention, as any change in their cover or biomass may impact the entire ecosystem (Kidron et al., 2012). Recently, they have been recognized as a major influence on desert terrestrial ecosystems (Xiao et al., 2014). However, the natural development of BSCs is slow (Allen, 1995; Belnap, 2003; Bowker, 2007) and susceptible to environmental factors as well as disturbing activities (Bu et al., 2013; Bowker, 2007; Muscha and Hild, 2006). Crust cover and biomass may be highly affected by surface stability and the residence time of soil moisture (Kidron et al., 2009). Therefore, studies on the spatial distribution patterns of BSCs are essential for performing field surveys and managing this resource, and they are also important for promoting the ecological functions of BSCs, including improved soil conditions and water conservation.

In this study, the distribution of BSCs in the wind–water erosion crisscross region, which is shaped by both water and wind erosions, of the Chinese Loess Plateau under complex conditions was analyzed using geostatistics and biostatistics methods based on field surveys and mapping, which is a new way to explore this phenomenon. We hypothesize that the distribution of BSCs has a significant relationship and correspondence with environmental conditions and their spatial pattern, as well as the spatial autocorrelation to some degree. For this

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objective, we selected a complete hill slope and conducted a comprehensive survey to ensure the integrity and validity of the data obtained by geographic information system (GIS), geo-statistics (GS), and canonical correspondence analysis (CCA) methods. CCA is the method that extracts the best synthetic gradients from field data on biological communities and environmental features, and it forms a linear combination of environmental variables that maximally separates the niches of the species (Klami et al., 2013). The results could provide a reference for the investigation and assessment of BSC resources and promote their field recovery and cultivation in this area.

2. Materials and methods

2.1. Study area

The study was conducted in the small watershed of Liudaogou (E110°21′–110°23′, N38°46′–N38°51′), which is 14 km west of Shenmu County in Shaanxi Province, China. The watershed covers an area of 6.89 km^2 and has an altitude of 1094–1274 m. The main channel is north–south orientated, 4.21 km in length, and belongs to the secondary tributaries of the Kuye River. The study area is located in a transition zone from Maowusu sandland and forest steppe to arid steppe on the Loess Plateau and is part of a typical water–wind erosion crisscross region associated with the transition from water erosion to wind erosion, where the annual erosion modulus reaches up to 10,000 t/km^2 (Cheng et al., 2007). The climate is temperate and semi-arid, and winter and spring are dry with less rain, more windblown sand and serious wind erosion of the soil, whereas frequent heavy rainfall occurs in summer and autumn, resulting in strong water erosion. The average annual temperature is 7–9 °C. The prevailing wind direction is northwesterly, and the average annual wind speed is 2.2 m/s. The average annual rainfall is 400 mm, and approximately 70–80% of the total rainfall occurs from June to September (Li et al., 2004). The major vegetation species in the watershed include sand sagebrush (*Artemisia desertorum* Spreng), Korshinsk peashrub (*Caragana korshinskii* Kom), Chinese silvergrass (*Stipa bungeana* Trin), alfalfa (*Medicago sativa* L.), bush clover (*Lespedeza davurica* (Laxm.) Schindl.), and Aertaigouwahua (*Heteropappus altaicus* (Willd.) Novopokr.). The east side of the watershed is mainly covered by loess, which accounts for 86.5% of the watershed area; the west side is generally covered by fixed dunes, which account for 13.5% of the watershed area (Jia et al., 1993).

2.2. Methods

2.2.1. Field survey and mapping

A typical ridge slope that has been fallow for more than 30 years was selected from the small watershed of Liudaogou (Fig. 1, red circle). A systematic survey on the spatial distribution of BSCs was conducted from June to October 2014, and the cover, thickness and shear strength of BSCs were surveyed in June and July. For accurate mapping, the survey was performed by plotless sampling (Fig. 2-A). Each field survey point was positioned using an eTrex HD handheld Global Positioning System (GPS). BSC cover within a radius of approximately 10 m around the survey point was investigated using the square grid method. The thickness (mm) and shear strength (kPa) of the BSCs were measured in situ using a caliper and pocket vane shear test apparatus (BWT2XZJL), respectively, and each measurement was repeated three to five times. Spatial distribution maps of the cover, thickness and shear strength of the BSCs were generated indoors using ArcGIS 10.1. The vegetation type and cover were surveyed by plotless sampling from mid-August to early September (Fig. 2-B), and a distribution map of 21 vegetation types was generated using ArcGIS 10.1. For soil sampling and analysis, a number of typical plots were selected from the survey area in early to mid-October (Fig. 2-C). The soil crust was carefully scraped off, and the 0–5-cm surface soil layer was collected using a cutting ring. The soil samples were transported to the laboratory and oven-dried at 105 °C for 24 h to measure the soil bulk density (g/cm^3) and water content (%). Sparse data points of soil bulk density and water content were interpolated and mapped by regression-Kriging using ArcGIS 10.1. Because soil water content was measured over a period of 15 days, the topsoil water content was first corrected by trend removal to eliminate the effect of daytime evaporation. The data were then interpolated by regression-Kriging to obtain a spatial distribution map of topsoil water content. To simulate solar radiation, the spatial distribution of solar elevation angles (SEAs) at 08:00, 10:00, 12:00, 14:00 and 16:00 on October 1 was mapped using the shading tool of ArcGIS 10.1 combined with data from a digital elevation model (DEM) of the survey area. The data were collected on October 1 because the concentrated reproductive period of mosses, a dominant species of local BSCs, occurs from September to November. Because of the potential effect of solar radiation on BSC reproduction, data from October 1 were used to determine the average solar radiation.

2.2.2. Statistical analysis

Based on the DEM and other basic maps of the Liudaogou watershed, the above-mentioned thematic maps of the BSCs, vegetation and soil were combined using the spatial analysis function of ArcGIS 10.1. These base maps were resampled and extracted by re-constructing 20 m × 20 m grids (Fig. 2-D). In total, 1342 plot data points each with 41 attributes were produced. Attributes included an environmental data matrix composed of 15 environmental indices, data regarding the thickness and shear strength of BSCs, and a species data matrix reflecting the cover of 24 vegetation species, including BSC cover. The correlations of the BSC indices (cover, thickness and shear strength) with environmental factors (e.g., topography, soils and simulated solar radiation) and vegetation communities were obtained via CCA using CANOCO 4.5. The CCA ordination results and a diagram illustrating the corresponding relationships were generated and then interpreted along with the spatial distribution maps.

CCA is a nonlinear multivariate direct gradient analysis method that combines correspondence analysis with multiple regression analysis. CCA regresses the results of each step of the calculation of environmental factors and then analyzes the species-environment relationships in detail (Braak, 1986). Because CCA ordination is based on a single-peak model, it has certain requirements for the distribution of species. Thus, a detrended correspondence analysis (DCA) on the species data must first be performed. According to the ordination results, if the length of the ordination axis with the longest gradient is less than 3, a linear model is optimal; if the length of the ordination axis is greater than 4, a single-peak model is optimal; and if the length of the ordination axis equals 3–4, both linear and single-peak models are suitable (Wang et al., 2014). In this study, DCA ordination was first performed on the attribute data of samples obtained by re-sampling and extraction. The length of the first ordination axis was 4.127, which is suitable for CCA ordination based on the single-peak model. The analysis results included statistical data and two-dimensional CCA ordination diagrams (Leps and Smilauer, 2003).

3. Results

3.1. Spatial distribution characteristics of BSCs

3.1.1. Spatial characteristics of BSC cover

The spatial distribution of BSCs exhibited clear differentiation. Fig. 3-A illustrates the distribution of BSC cover. Combined with the spatial distribution of soil types (Fig. 3-B), the majority of BSCs was found to occur in the sand area and showed a wide and continuous distribution. Statistical data (Table 1) showed that the mean cover was greater than 30% in the sand area. The distribution of BSCs was discrete and sporadic in the loess area, as BSCs were found mostly at the edges of the slope with generally less than 20% cover. The results obtained from GS + 9.0 geostatistical software (Fig. 4) showed that the spatial distribution of