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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

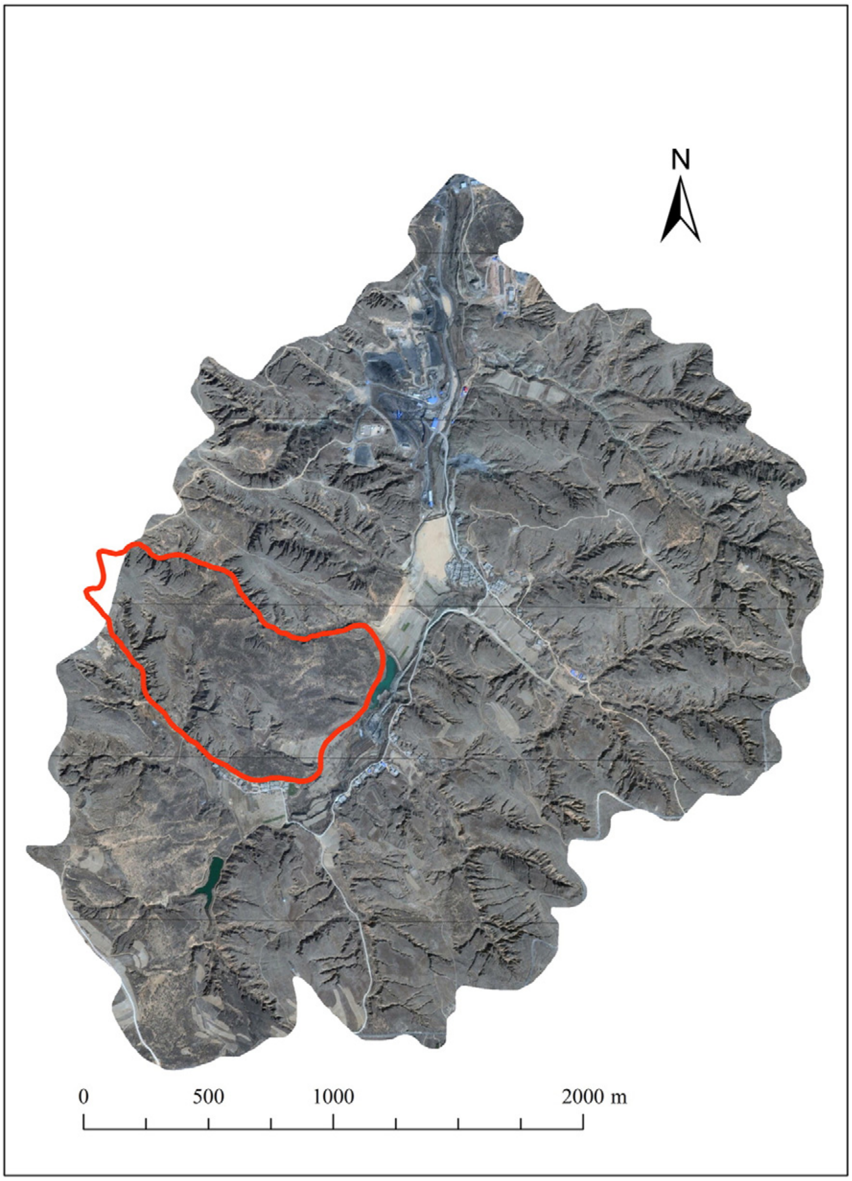

Fig. 1. Remote sensing image of the Liudaogou small watershed on the Chinese Loess Plateau.

BSCs had significant spatial autocorrelation in the sand area ($C/(C_0 + C) = 0.898$). According to the isotropic assumption, the maximum distance of spatial autocorrelation (range, h) was obtained by fitting the semivariance function of spatial variations using an exponential model, i.e., 90–100 m. On the distribution map of BSC cover, we assumed that BSCs had clear locations of origin where biocrusts initially inhabit or colonize the sand area (Fig. 3A, yellow area). These locations of origin were mostly at low-lying junctions between the sand and loess areas where soil water and nutrient conditions are highly favorable for the development of BSCs. The BSC cover in the locations of origin reached 90% or higher.

3.1.2. Spatial variability of BSC thickness and shear strength

The survey results showed that both the thickness and shear strength of the BSCs had moderate spatial variability, although the overall differences were not significant. Fig. 5-A and B depicts the spatial distribution of the thickness and shear strength of the BSCs. In the survey area, BSCs were generally 12–14 mm thick and had a shear strength of 4–6 kg/cm^2. In the locations of origin, the BSC thickness reached 2 cm or greater, and the shear strength reached 0.7 kg/cm^2 (ca. 70 kPa). Statistical data (Table 1) showed that the mean thicknesses of BSCs in the sand and loess areas were 13.1 and 12.8 mm, respectively, and the corresponding average shear strengths were 4.96 and 4.76 kg/cm^2, respectively. The t-test results showed that there were no significant differences in the mean thickness or shear strength of BSCs between the loess and sand areas ($P > 0.05$).

3.2. Relationship between BSC distribution and environmental factors

3.2.1. Integrated interpretation of CCA results

The CCA analysis results (Table 2) showed that the spatial distribution of BSCs and vascular plants was most highly correlated with the first ordination axis (horizontal) ($r = 0.910$), which explained 60.7% of the species-environment relations. The other axes had lower correlations with species distribution, and the four axes explained 87.8% of the species-environment relations. Although the results passed the Monte Carlo permutation test ($P = 0.002$), they could only explain 22.2% of the variation in species distribution, indicating a poor predictive ability. However, the results had a strong ability to reconstruct the species-

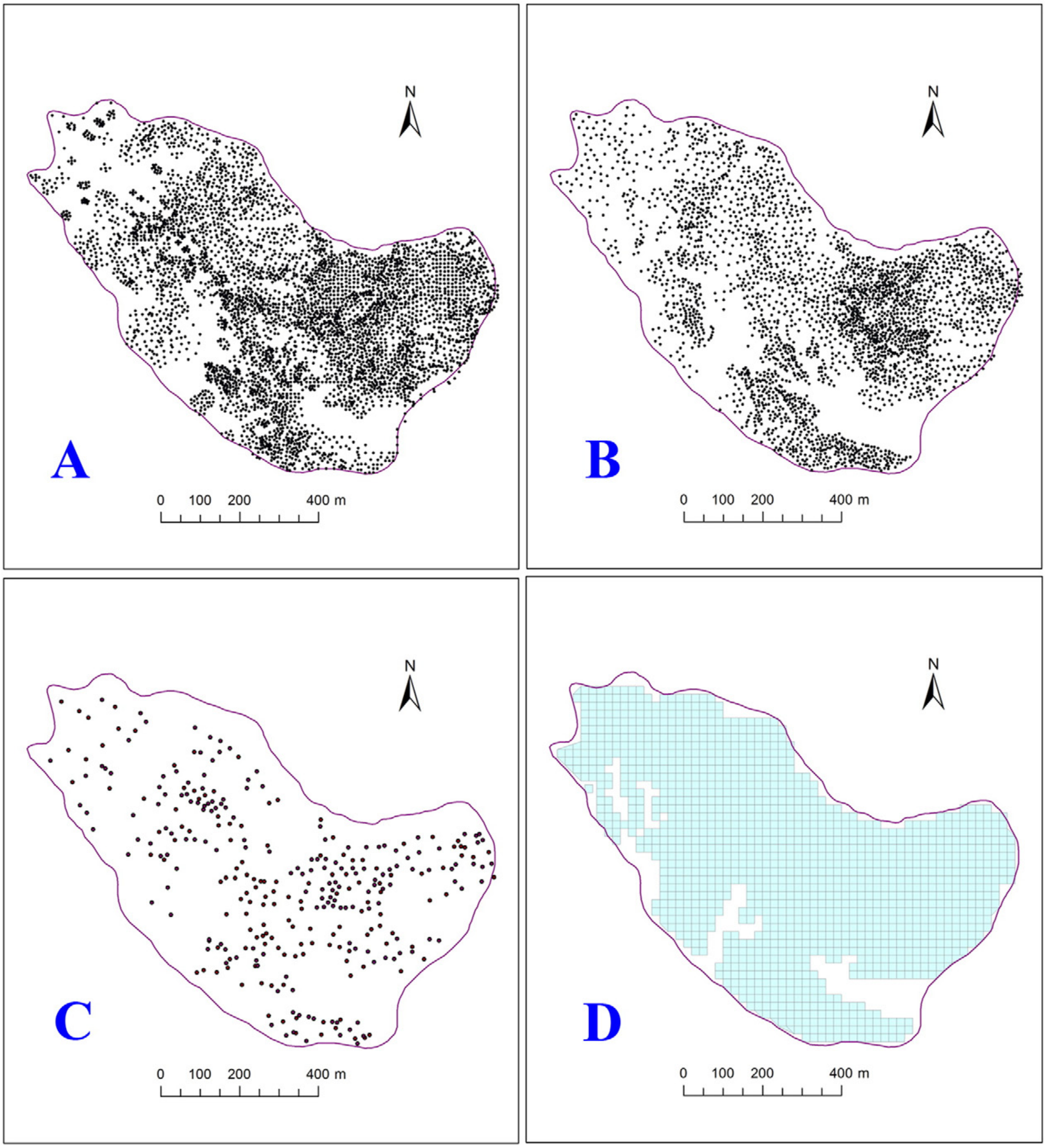

Fig. 2. Sampling points for biological soil crusts (BSCs) (A), vegetation (B), soil (C) and resampling grid (D).

environment relations; thus, they were meaningful for interpreting the species-environment relations.

The ordination diagram (Fig. 6) shows that the vegetation communities were generally divided into four types of shrub-herb communities (psammophytic, loessial, sciophytic and heliophytic) and one type of *Populus simonii* woodland community. These vegetation communities mainly included *A. desertorum*, *Salix cheilophila* + *A. desertorum*, *C. korshinskii* + *S. bungeana*, *Artemisia scoparia*, *Heteropappus hispidus* + *Setaria viridis*, *Poa sphondylodes* and *P. simonii*. Changes in the environmental gradient were also observed from the four ordination axes. The first ordination axis (horizontal) was closely correlated with soil type and bulk density. Along the direction of the horizontal axis, the left side represents the sand environment and corresponds to psammophytic plant communities dominated by *A. desertorum*, *S. cheilophila* and *P. simonii*, whereas the right side represents the loess environment and corresponds to plant communities dominated by *C. korshinskii* and *S. bungeana*. The longitudinal axis was closely correlated with aspect, slope and solar radiation. The upper section of the longitudinal axis mainly represented the shady and steep slope environment and corresponded to plant communities such as *Poa annua*, *P. sphondylodes* and *Artemisia sacrorum*, whereas the lower section mainly represented the sunny and gentle slope environment and corresponded to plant communities such as *H. hispidus* and *S. viridis*.

3.2.2. Relationship between BSCs and topographic factors

The CCA ordination diagram displays the relationships between BSC (cover, thickness and shear strength) and topographic factors, such as slope, aspect, elevation, topographic wetness index (TWI), stream power index (SPI) and sediment transport index (STI). TWI, SPI and STI are useful integrated topographic variables for characterizing

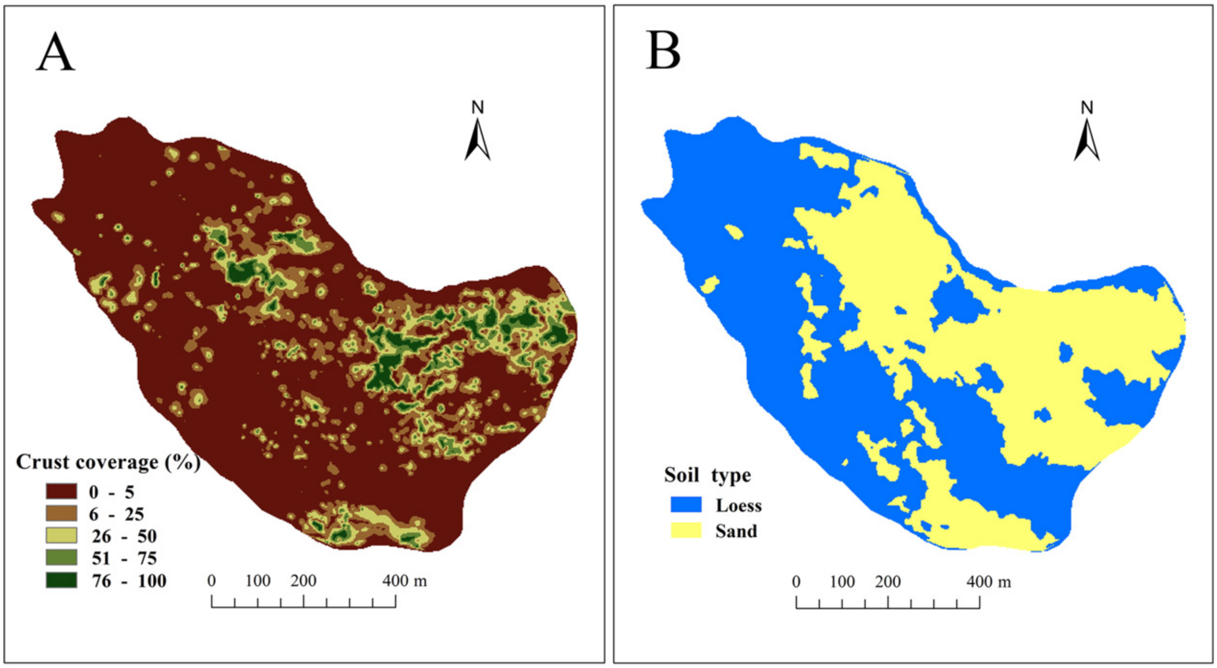

Fig. 3. Spatial distribution of biological soil crust (BSC) cover and soil types.

water and sediment transport in specific landscapes (Lian et al., 2008). The cover, thickness and shear strength of BSCs had good consistency and were negatively correlated with slope, aspect and elevation (moderate) but positively correlated with TWI (significant) and SPI (weak). Few correlations were observed between the BSC indices and STI.

Additionally, the solar radiation characterized by average SEA also influenced BSC distribution to a certain degree due to the topography factor. The CCA ordination diagram shows that BSC cover was strongly positively correlated with SEA at 08:00. Thus, BSCs were preferentially distributed in areas with relatively high SEA at 08:00 but almost unrelated to SEA at 10:00 in early October. Thereafter, BSC cover showed a negative correlation with SEA at 12:00, 14:00 and 16:00 as well as with average SEA (hs) during the day.

3.2.3. Relationship between BSCs and soil factors

The CCA ordination diagram shows that BSC cover (JPGD) was more closely correlated with sandy soil compared with loess soil. This result indicated that BSCs preferentially grow in sandy environments, which is consistent with field observations. The soil regression analysis revealed that soil type explained 20% of the spatial variation in BSCs ($R^2 = 0.199$). Moreover, the CCA ordination diagram shows that the thickness and shear strength of the BSCs were positively correlated with soil bulk density.

3.2.4. Relationship between BSCs and plant communities

According to the results of the field survey and the CCA ordination diagram, the majority of BSCs were distributed in psammophytic and sciophytic herbaceous plant communities (dominated by *A. desertorum*, *P. sphondylodes* and *Eragrostis minor*) and woodland communities (*P. simonii* as the dominant and constructive species). In these plant communities, BSC cover was generally greater than 30%–40%.

Regarding the relationship between BSC cover and vegetation cover, the field survey found that BSC cover exhibited a clear positive correlation with *A. desertorum* cover, whereas a clear negative correlation was found for *C. korshinskii* and *S. bungeana* cover. After the removal of soil type (a factor closely related to BSC cover), a partial correlation analysis of the species data revealed that none of the correlations between BSC cover and various vegetation species were statistically significant. However, the results still indicated certain correlations between BSCs and vegetation cover, although the correlations were statistically weak. The correlations with *A. desertorum*, *P. simonii*, *Chenopodium aristatum* and *E. minor* were positive ($r = 0.191$, 0.174, 0.248 and 0.224, respectively), but the correlations with *C. korshinskii*, *S. bungeana* and *H. hispidus* were negative ($r = -0.242$, -0.128 and -0.130, respectively).

Furthermore, small and accidental species in the communities cannot be ignored because they could be reflective of the condition of the inorganic environment. For example, in this study, it was found that *Enneapogon borealis* was much more likely to grow in relatively humid

Table 1
Comparison of the growth characteristics of biological soil crusts between sand and loess study areas.

Growth index	Sand area		Loess area		t-test
	Mean	Std. error of the mean	Mean	Std. error of the mean	
BSC coverage	32.58	0.726	22.01	1.16	−7.724**
Thickness	1.31	0.042	1.28	0.153	0.589 n.s.
Shear strength	4.96	0.201	4.76	1.104	0.949 n.s.

BSC: Biological soil crust.
n.s.: not significant ($P > 0.05$).
** Highly significant difference ($P < 0.01$).

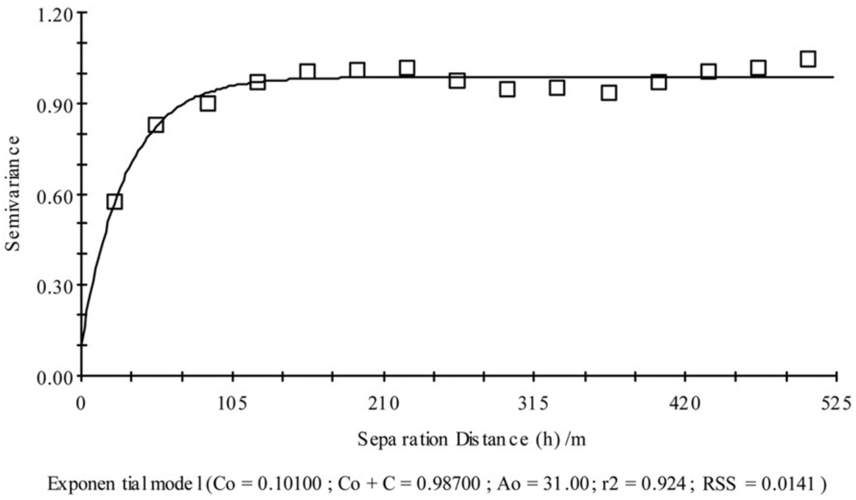

Fig. 4. A semivariance function model of spatial autocorrelations of biological soil crusts (BSCs).

sand patches in the loess area; therefore, locations that support the growth of *E. borealis* also support the development of BSCs.

4. Discussion

4.1. Reasons for low spatial variation in the thickness and shear strength of BSCs

The thickness and shear strength of BSCs exhibited non-significant spatial variation in the study area, which may have been caused by one of three factors. First, the thickness of BSCs may be primarily affected by the particular stage of BSC development (Zhao et al., 2006). In the present study, the survey area had been fallow for more than 30 years, indicating that BSCs in all locations were fully developed. Theoretically, BSCs develop to reach a stable thickness, although minor differences were observed in the BSCs in various areas. Second, errors inevitably caused by field measurements could mask the differences in BSC thickness caused by environmental factors. “BSC thickness” refers to the thickness of BSCs that are naturally separated from the subsoil (Xiao et al., 2007). However, it is impossible to guarantee the absolute separation of BSCs from the subsoil or obtain an absolutely rigid and flat separation surface in practice. Because changes in the thickness of BSCs were small, sampling and measurement errors were likely to have a greater effect on the thickness of BSCs and were difficult to control. Third, the thickness of BSCs at local sites varies widely and can even cause a pure nugget effect. In addition, the shear strength of BSCs could be affected by various practical situations. Although this study attempted to select relatively intact and typical BSCs for measurement, it was difficult to ensure that the BSCs were not destroyed when the pocket shear tester was pushed into the crust layer. Moreover, the wetness of the crust layer has a substantial impact on measurement results.

4.2. Influence of topography on the distribution of BSCs

Topography (e.g., slope, aspect and elevation) is an important factor that affects the development and spatial distribution of BSCs. First,

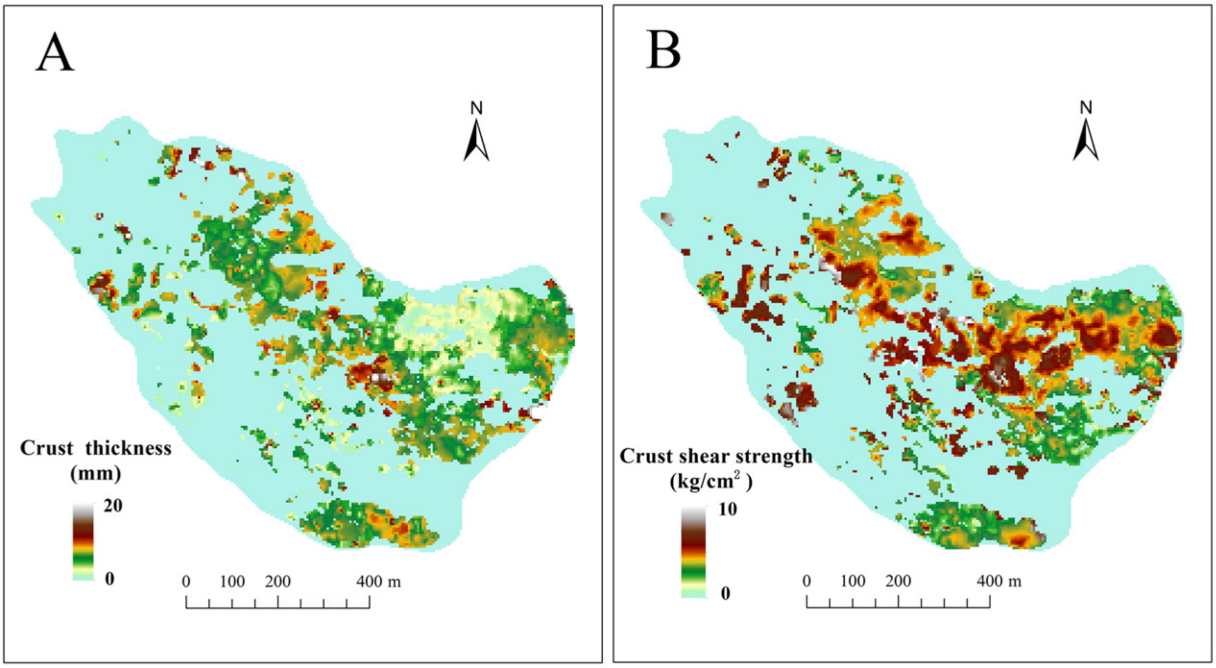

Fig. 5. Spatial distribution of the thickness and shear strength of biological soil crusts (BSCs).

Table 2
Canonical correspondence analysis (CCA) of vegetation and environment.

Axes	1	2	3	4	Total inertia
Eigenvalues	0.553	0.106	0.094	0.047	3.602
Species–environment correlations	0.910	0.639	0.551	0.484	
Cumulative percentage variance					
of species data	15.4	18.3	20.9	22.2	
of species–environment relation	60.7	72.3	82.6	87.8	

topography can be used to determine the spatial distribution of light-heat-water conditions directly related to the development of BSCs; second, topography can also help to propagate and spread BSCs. The former determines the spatial variability of BSCs, and the latter controls the continuity of BSC spatial distribution.

In this study, BSC cover was negatively correlated with slope degree, aspect and elevation, indicating that BSCs are more often found on gentle shady slopes at low elevations. There was a significant positive correlation between BSC cover and TWI, indicating that BSCs are more often found in soils with long-term stability and relatively high humidity. The weak positive correlation between BSC cover and SPI might have been caused by a certain level of correlation between runoff distribution and the propagation and spreading direction of BSCs. Almost no correlations were observed for BSC cover and STI, which may have been caused by the strong positive correlation between STI and slope, whereas BSCs tended to be found on gentle slopes. These results indicate that SPI is more suitable than STI for use in predictions of the spatial distribution of BSCs.

Considering the relevant findings of other scholars (Jia et al., 2012; Zhang et al., 2009; Zhao et al., 2010), we suggest that the relation between BSC cover and SEA is associated with the time of day at which BSCs are active. At 08:00, a greater amount of dew condensation water was present, and BSC-associated organisms became activated and began performing photosynthesis; thus, BSCs tended to grow in places with relatively high SEA at 8:00 am to gain more solar energy. By 10:00, the dew had evaporated completely and BSC activity was reduced; thus, SEA had a limited relationship with the distribution of BSCs. In the afternoon, BSCs tended to grow in shady slope areas.

4.3. Influence of soil on the distribution of BSCs

Soil is one of the most direct and critical factors that affects the development and spatial distribution of BSCs, and soil type partially determines the community morphology and landscape ecological pattern within the survey area. Although sand is a good matrix for the development of BSCs, sandier soil does not necessarily provide a better growth environment for BSCs. A field survey revealed that BSCs showed improved growth in sand mixed with loess in a certain ratio. Similarly, the CCA ordination diagram shows that BSCs had an optimal range along the direction of soil bulk density.

It should be noted that soil has multiple effects on BSCs (Michaud et al., 2013; Wu et al., 2003; Zhao et al., 2006). Topsoil water content,

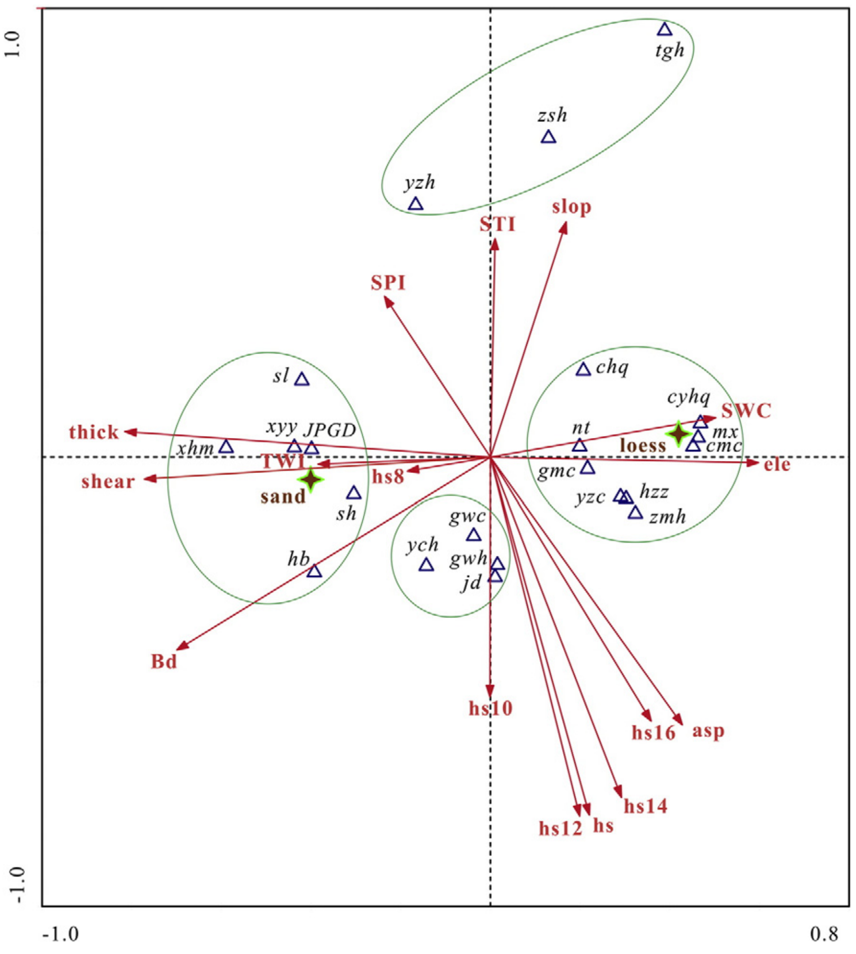

Fig. 6. Canonical correspondence analysis ordination diagram illustrating the relationships of biological soil crusts (BSCs) with vegetation communities and environmental factors Arrows indicate environmental factors. Abbreviations are as follows: ele, elevation; SWC, soil water content; asp, aspect of slope; slop: degree of slope; Bd, soil bulk density; hs8–12, solar elevation angle at 08:00–12:00; TWI, topographic wetness index; SPI, stream power index; STI, sediment transport index; JPGD, cover of biological soil crusts; thick, thickness of biological soil crusts; shear, shear strength of biological soil crusts. Asterisks represent soil types (loess and sand); triangles represent plant species (codes defined in Appendix Table 1).

mainly determined by soil water retention capacity, has a direct influence on BSCs. Soil bulk density indirectly impacts BSCs through porosity, mechanical composition and soil structure. Other more essential direct factors (e.g., soil pH, soil nutrient content) influencing BSCs must be further studied.

4.4. Influence of vegetation communities on BSC distribution

The relationships and interaction mechanisms between plant communities and BSCs are complex. Studies have shown that BSCs affect the seed bank of vascular plant communities by increasing the seed bank reserves and preventing the germination of certain species (Su et al., 2006, 2007a, 2007b); however, these effects are also related to the type of BSC and the life-form of the species. Vascular plants also affect BSCs. For example, the development of BSCs is affected by the canopy structure, population density, root depth, plant litter and secretions from dominant and constructive species. Long-term interactions and natural selection lead to niche displacement and species separation, and relatively stable organic community structures are formed.

It is worth noting that the relationship between BSCs and plant communities may not be direct in a number of cases. It is more likely that BSCs share some habitat preferences with some plant species, and have divergent habitat needs compared to other plant species. For example, BSCs preferentially grow in sandy environments and *A. desertorum* is a typical psammophytic plant; therefore, BSCs and *A. desertorum* are significantly correlated. A partial correlation analysis after the removal of the soil matrix also revealed that a weak correlation occurred between BSC distribution and vegetation community type, which is consistent with the results presented here.

4.5. Limitations and prospects

The CCA statistical analysis method was developed in the 1980s (Braak, 1986) and has been frequently used in ecological studies (Zhang, 2004). A CCA can reveal intuitive and detailed relationships between vegetation communities and the environment. In the present study, an attempt was made to introduce CCA into the BSC distribution survey. Based on the field conditions, a plotless survey and sampling were used in combination with GIS and geostatistical analyses. The spatial distribution characteristics and patterns of BSCs in the wind–water erosion crisscross region of the Loess Plateau were preliminarily discussed, and satisfactory results were obtained. However, several issues were observed in this study. After mapping of the field survey data, the extraction and resampling based on map data often resulted in lower values compared with the measured data because of the image interpolation algorithm. In this study, most distribution maps were generated by natural neighbor interpolation. Although this approach effectively reconstructed the spatial distribution of BSCs and vegetation, the overall cover was underestimated by approximately 10%. Thus, this method would cause certain systematic biases and inconsistencies in interpreting results from remote sensing images. Images precisely constructed with densified points are highly consistent with remote sensing images. However, this approach involves a substantial workload and is only suitable for surveying spatial distributions on a small scale. Therefore, our next step is to combine ground surveys with remote sensing image interpretation to study the spatial distribution of BSCs and associated influencing factors on a watershed or regional scale. Such work will provide a solid foundation for research on the ecological functions of BSCs and their effects on windbreaks and sand-fixation as well as their influence on carbon sequestration in arid and semi-arid regions (Fang et al., 2008; Grote et al., 2010; Monroy et al., 2011; Strauss et al., 2012; Yang et al., 2001).

Furthermore, the CCA statistical analysis method is based on correspondence analyses and reciprocal averaging (Zhang, 2004); however, the greatest disadvantage of this method is that the second ordination axis is a secondary deformation of the first axis in many cases, which creates an arch effect (Jia et al., 2007). To address the issue of arch effects, Braak (1987) proposed a detrended canonical correspondence analysis (DCCA), which produces better results than CCA. Thus, the DCCA can be used in cases of significant arch effects.

5. Conclusions

Our study showed that GIS, GS and CCA effectively reveal the relationship between biological soil crusts (BSCs) distribution and environmental factors. Most striking, biological soil crusts (BSCs) attain higher continuous coverage in sandy areas, but a lower and sporadic distribution in loess areas. The spatial differentiation of biological soil crusts' (BSCs) thickness and shear strength is not significant, the minor variations in these values are likely to be mostly related to the developmental age of biological soil crusts (BSCs) which was constant across the study area. At the hillslope scale, the development or spatial distribution of biological soil crusts (BSCs) indicates an obvious selectivity for soil type, topography, and vegetation communities, and biological soil crusts (BSCs) tend to develop in shady desert plant communities where the slope is gentle and the soil moisture level is higher. *A. desertorum* shrubland and *P. simonii Carr.* woodland are the ideal developmental habitats for biological soil crusts (BSCs). In addition, the distribution of biological soil crusts (BSCs) has a significant relationship with solar elevation at 08:00 am.

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Appendix A

Appendix Table 1
Vegetation species and their codes in the survey area.

Family	Genus	Species	Code
Compositae	*Artemisia* Linn. Sensu stricto, excl. Sect. Seriphidium Bess.	*A. desertorum* Spreng. Syst. Veg.	sh
		A. sacrorum	tgh
		A. capillaries	ych
		A. scoparia Waldst. et Kit.	zmh
	Chenopodium Linn.	*C. aristatum* L.	cl
	Heteropappus Novopokr.	*H. altaicus* (Willd.) Novopokr.	gwh
Leguminosae	*Astragalus* Linn.	*A. melilotoides* Pall	chq
		A. scaberrimus Bunge	cyhq
	Hedysarum Linn.	*H. scoparium* Fisch. et Mey.	hb
	Lespedeza Michx.	*L. davurica* (Laxm.) Schindl.	hzz
	Medicago Linn.	*M. sativa* L.	mx
	Caragana Fabr.	*C. korshinskii* Kom.	nt
	Oxytropis DC.	*O. bicolor* Bunge	jd
		O. racemosa Turcz.	jd
Gramineae	*Stipa* Linn.	*S. bungeana* Trin.	cmc
	Enneapogon Desv. ex Beauv.	*E. borealis*	gmc
	Setaria Beauv.	*S. viridis* (L.) Beauv.	gwc
	Eragrostis Wolf	*E. minor* Host	xhm
	Cleistogenes Keng	*C. caespitosa* Keng	yzc
		C. squarrosa (Trin.) Keng	yzc
	Poa L.	*P. sphondylodes* Trin.	yzh
		P. annua L.	zsh
Salicaceae	*Salix* L.	*S. cheilophila*	sl
	Populus L.	*P. simonii* Carr.	xyy

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