

Spatial heterogeneity of soil and vegetation characteristics and soil-vegetation relationships along an ecotone in Southern Mu Us Sandy Land, China

Yingzhong Xie¹ · Kaiyang Qiu² · Dongmei Xu¹ · Xiangfeng Shi³ · Tuoye Qi^{4,5} · Richard Pott²

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Abstract

Purpose This study aims to examine the changes in the spatial heterogeneity of soil properties at different soil layers, the spatial heterogeneity of soil and vegetation characteristics along an ecotone, and soil-vegetation relationships along the ecotone in a critical area of desertification.

Materials and methods A study site was established across a *Lespedeza potaninii* (dominant) community (*LPC*) and an *Artemisia ordosica* (dominant) community (*AOC*), with the ecotone between these two communities. In this study, “along the ecotone” means from *LPC*, via the ecotone, and then to *AOC*. Three parallel transects (300-m long) were arranged at 50-m intervals along the site. Along each transect, at 10-m

spacings, 1 m×1-m quadrats were marked for the vegetation survey and soil sampling. Soil samples were analyzed in the laboratory after natural air-drying. Data analyses were conducted with a combination of classical and geostatistical methods. **Results and discussion** In most cases, species importance values and soil properties changed significantly ($P<0.05$) along the ecotone. Most soil and vegetation variables were moderately spatially autocorrelated. Kriging interpolated maps showed patch patterns of soil chemical properties. The $C/(C_0+C)$ values of soil properties were larger at 5–10-cm than those at 0–5-cm. Vegetation characteristics were mainly positively correlated with soil organic carbon (*SOC*), total nitrogen (*TN*), and electrical conductivity (*EC*). *TN* at 0–5-cm (*TN1*), *EC* at 0–5-cm (*EC1*), and available potassium at 5–10-cm (*AK2*) were selected as the predictors for plant species richness and diversity in the stepwise regression analysis between vegetation characteristics and soil properties. **Conclusions** Soil nutrients decreased significantly ($P<0.05$) along the ecotone. Soil and vegetation properties had moderate spatial heterogeneity. Soil properties had a stronger spatial heterogeneity at subsurface layers compared to surface layers. *TN1*, *EC1*, and *AK2* were the predominant factors for the plant community structure along the ecotone in the critical area of desertification.

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- ✉ Yingzhong Xie
xieyz@nxu.edu.cn
- ✉ Kaiyang Qiu
kaiyang588@sina.com
- ✉ Richard Pott
pott@geobotanik.uni-hannover.de

- ¹ Institute of Grassland Sciences, Ningxia University, Yinchuan 750021, P.R. China
- ² Institute of Geobotany, Leibniz Universität Hannover, 30167 Hannover, Germany
- ³ Institute of Design for Agricultural Survey in Ningxia, Yinchuan 750002, P.R. China
- ⁴ School of Agriculture, Ningxia University, 750021 Yinchuan, P.R. China
- ⁵ Institute of Ecology, Evolution and Diversity, Goethe University Frankfurt am Main, 60438 Frankfurt am Main, Germany

Keywords Community structure · Geostatistics · Semivariogram · Soil nutrient · Species diversity

1 Introduction

The spatial heterogeneity of soil and vegetation properties has received much attention over the last few decades, with in-depth studies in different ecosystems (Li et al. 2011;

Lakhankar et al. 2010; Dick and Gilliam 2007; Fraterrigo et al. 2005; Jackson and Caldwell 1993a). It has been taken as a useful index for indicating desertification in grasslands in arid and semiarid regions (Schlesinger et al. 1990, 1996), and also on field scales (Su et al. 2006). Previous studies showed that variations in soil nutrient distribution could change plant community composition and species diversity through the interactions between soil nutrient spatial heterogeneity and variability patterns of biotic factors (plant and heterotrophic biota) not only in forest ecosystems (Fraterrigo et al. 2005), but also in degraded sandy grassland (Su et al. 2006).

Spatial pattern analysis is an essential component of spatial heterogeneity studies on soil properties and vegetation characteristics. It was conducted in several studies for both soil and vegetation characteristics (Jackson and Caldwell 1993b; Schlesinger et al. 1996; Yavitt et al. 2009; Strand et al. 2007; Dick and Gilliam 2007; Zuo et al. 2010). These studies analyzed the spatial patterns of soil and/or vegetation characteristics in different ecosystems using geostatistical methods. They provide us with important insights into understanding spatial dependence, variability magnitudes, autocorrelation scales, and distribution features, all of which are very useful factors that allow us to identify the spatial traits and heterogeneity of soil and vegetation variables.

However, relatively few studies concerning the horizontal spatial heterogeneity of soil properties for different soil layers have been conducted. Franz et al. (2011) documented that soil resource availability and woody vegetation organization can be affected by heterogeneity in soil depth. But, it is still unclear how horizontal spatial heterogeneity changes between different soil layers. There is also a paucity of knowledge especially on the spatial heterogeneity of soil properties concerning both horizontal and vertical levels along the ecotone in the critical area of desertification.

Recent studies have shown that several factors, such as grazing (Su et al. 2006), land use (Zhou et al. 2008; Gilliam and Dick 2010), timber harvest (Fraterrigo et al. 2005), microhabitat (Frouz et al. 2011), and wind erosion (Li et al. 2008), can play an important role in affecting the spatial heterogeneity of soil properties and vegetation characteristics in different study sites. However, there is still a lack of knowledge about how soil and vegetation spatial heterogeneity change along the ecotone in desertified grassland, how community composition and soil properties change, and what the soil-vegetation relationships along the ecotone in the critical area of desertification are.

In order to get a better understanding of these issues, we investigated a community ecotone in Southern Mu Us Sandy Land, northwestern China. The study area was located in the transitional zone between typical steppe and sandy land. It was one of the critical areas of desertification found by Xu (2007), who quantitatively determined the typical steppe—

sandy land boundary on a relatively large scale (110-km) with moving split-window techniques in the southern fringe of Mu Us Sandy Land. The results of Xu's study allowed a breakdown of levels of desertification defined by boundaries correlating with peaks in the graphical representations of parameters such as soil particle size and plant importance values plotted against square Euclidean distance. These boundaries were considered to be critical areas of desertification because they were the transitional areas of adjacent ecosystems, responding more sensitively to natural environmental changes and human disturbances. Our study area was located at one of the boundaries mentioned above and identified as being "moderate desertification grassland." This site is, therefore, ideal for grassland desertification studies.

The study site was located in Yanchi County of Ningxia Hui autonomous region, China. This region suffered from severe desertification due to a combined effect of natural conditions and human activities. Desertification affected not only the socioeconomic development but also the environment and human life in this region (Zhou et al. 2010). Moreover, desertification resulted in great changes in soil and vegetation characteristics in this area. Soil organic carbon, total nitrogen, and available nitrogen all decreased clearly with the aggravation of desertification; the dominant plant species also changed from steppe species to psammophyte and shrubs in this desertification process (Xu et al. 2012). Desertification is therefore a socio-eco-environmental problem that need much attention of study. This study will provide a scientific basis for the spatial heterogeneity of soil and vegetation characteristics and soil-vegetation relationships along the ecotone related to desertification.

The ecotone in this study is in the middle of two plant communities, i.e., *Lespedeza potaninii* community (LPC) and *Artemisia ordosica* community (AOC). The ecotone is a restricted area within our study site. To clarify the terminology used in this study, "along the ecotone" means "from LPC, via the ecotone, and then to AOC." In LPC, *L. potaninii* and perennial herbs were the dominant plant species, while in AOC, herbaceous plants were replaced by *A. ordosica*; *L. potaninii* was still one of the dominant species. Species composition changes can lead to a variability in the spatial dependence of soil nutrients (Gross et al. 1995). Soil nutrients were believed to be gathered under the canopy of shrubs (Su et al. 2005), which provides a good environment for the colonization of herbaceous plants (Shumway 2000; Holmgren and Scheffer 2001). The establishment of shrubs is therefore beneficial for the settlement of herbaceous species (Zuo et al. 2009b). Although this is clear for a temporal process of community succession, more information is still needed about the spatial process when shrubs and herbs come together. An investigation into changes in soil nutrients along the ecotone as herbs are gradually replaced by shrubs is therefore necessary. Simultaneously, soil-vegetation relationships along the

ecotone are also valuable for a better understanding of the spatial process of community change.

Based on the problems mentioned above, we have investigated three hypotheses in this study: (1) soil chemical properties have different heterogeneity features in surface and sub-surface soil layers; (2) soil nutrients decrease clearly along the ecotone with the changes of plant community composition from the *L. potaninii* community (LPC) to the *A. ordosica* community (AOC); and (3) some of the soil properties have intimate relationships with vegetation indices along the ecotone. This study on the spatial heterogeneity in vegetation characteristics and soil chemical properties along the ecotone located in the critical area of desertification on a relatively small scale (300 m) will improve our understanding not only of grassland desertification, but also of grassland management in arid and semiarid regions.

2 Materials and methods

2.1 Site description

The study was conducted in Sidunzi village (37° 45′–37° 47′ N, 107° 15′–107° 18′ E) in Yanchi county, Ningxia, northern China. The regional vegetation map is shown in Fig. 1 (Compilation committee of the Ecological Construction Annals of Yanchi County 2004). This area is in the southwestern fringe of Mu Us Sandy Land. Climate conditions in this area provide the basic forces for land desertification. At the same time, grazing pressure and vegetation changes exacerbate the desertification development. This area has a typical mid-temperate and semiarid continental climate, with a multi-year annual average temperature of 7.7 °C, the highest monthly average temperature of 22.5 °C in July, and the lowest monthly average temperature of –8.9 °C in January. The annual average precipitation is 300 mm, which is mainly received in the growth season between June and August. The annual mean evaporation capacity is 2136 mm, and the nonfrost period has a duration of 162 days. The soil in this area is mainly light sierozem with some aeolian sandy soil. The vegetation consists of some annual and perennial steppe grasses and forbs, and semishrubs, including *L. potaninii* Vass. (semishrub), *A. ordosica* Krasch. (semishrub), *Stipa bungeana* Trin. (perennial grass), *Agropyron mongolicum* Keng (perennial grass), *Astragalus melilotoides* Pall. (perennial legume), *Cleistogenes squarrosa* (Trin.) Keng (perennial grass), and *Artemisia scoparia* Waldst. et Kit. (annual forbs).

As mentioned above, the study site is across the *L. potaninii* (dominant) community (LPC) and the *A. ordosica* (dominant) community (AOC), with the ecotone in the middle. The dominant species in the LPC were *L. potaninii* and *A. mongolicum*. The importance value (IV) of *L. potaninii* in the LPC was 22.02, and that of *A. mongolicum*

was 13.94 (the total IVs of all plant species in the community is 100) (Table 1). Both *L. potaninii* and *A. mongolicum* are high-quality forage plants. *L. potaninii* is a herb-like semishrub and is compatible with other herbaceous plants. *A. mongolicum* is a perennial grass species. Except for *A. mongolicum*, there were several other grass species, such as *S. bungeana* and *Leymus secalinus*, the IVs of which are 9.05 and 7.28, respectively. Perennial grass is an important plant group in the LPC with the total IV of 37.19. There was few *A. ordosica* in the LPC. However, it grew rapidly in the ecotone and became the dominant species in the AOC. *A. ordosica* is a semishrub species and is much larger than any other species in this study site. Some species, especially the grass species, could not be found any more in the AOC, while *A. ordosica* became larger with more individuals in the ecotone and the AOC (Fig. 2). The IV of *A. ordosica* increased to 30.71 and 36.45 in the ecotone and in the AOC, respectively.

The plant composition in the LPC, the ecotone, and the AOC showed that the land in the LPC is less desertified than that in the ecotone and the AOC. The perennial grasses in the LPC are the typical grassland species, indicating a relatively less desertification in this community. But, the land in the LPC was also desertified to some extent as *L. potaninii* is a species prone to grow in desertified areas. However, *A. ordosica* is a pioneer species for sand fixation and is an indicator for land desertification. *A. ordosica* replaced perennial grass species to be the dominant species in the AOC, suggesting that the desertification became aggravated.

2.2 Field survey and sampling

In 2009, a 300 m × 100-m site was established at the beginning of August, which is in the annual best growth season for vegetation. Three parallel transects were laid out in this study site, starting from within the *L. potaninii* (dominant) community and ending within the *A. ordosica* (dominant) community, with the ecotone of the two communities in the middle. The three transects were 300-m long with a 50-m interval between the adjacent two transects (Fig. 3). Along each transect, 30 1 m × 1-m quadrats for herbs were established at 10-m intervals for the vegetation survey. For each quadrat, the number of plant species was recorded, and four plant indices comprising plant height, abundance, cover, and frequency for each plant species were also noted. Cover was measured using 100 points homogeneously distributed in the quadrat. The percentage of a specific species touched by the vegetation investigation stick in the 100 points was taken as the cover of the species. Frequency was measured for ten times randomly distributed around the quadrat using an iron ring with a diameter of 0.5 m. All species found in the ring were recorded, and the number of times a specific species appeared across the 10 times was taken as its frequency. At the same time, three soil samples were taken from locations triangularly distributed in

Vegetation distribution map in Yanchi County of Ningxia Autonomous Region, China

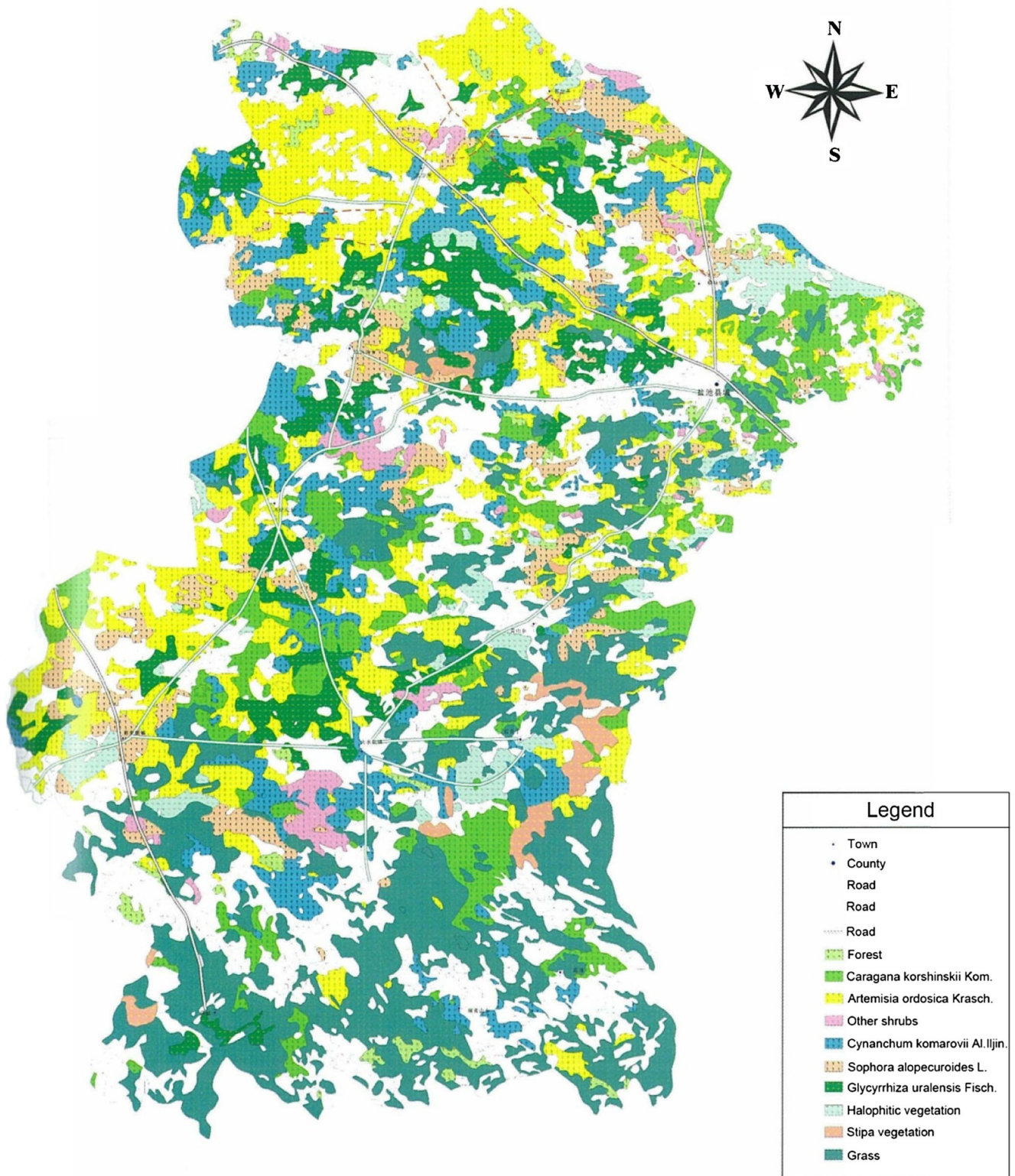


Fig. 1 Vegetation distribution map in Yanchi County of Ningxia Autonomous Region, China (from Compilation committee of the Ecological Construction Annals of Yanchi County 2004, changed)

Table 1 Changes of plant species importance values (*IVs*) along the ecotone of *L. potaninii* (dominant) community and *A. ordosica* (dominant) community in Southern Mu Us Sandy Land, China

Species	Abbreviation	Life form	<i>LPC</i>	<i>LPC-AOC</i>	<i>AOC</i>
<i>Lespedeza potaninii</i> Vass.	<i>Lp</i>	<i>PS</i>	22.02	29.87	26.46
<i>Artemisia ordosica</i> Krasch.	<i>Ao</i>	<i>PS</i>	5.30	30.71	36.45
<i>Stipa bungeana</i> Trin.	<i>Stb</i>	<i>PG</i>	9.05	1.45	0.00
<i>Agropyron mongolicum</i> Keng	<i>Agm</i>	<i>PG</i>	13.94	0.00	0.00
<i>Astragalus melilotoides</i> Pall.	<i>Asm</i>	<i>PL</i>	2.36	2.65	2.11
<i>Cleistogenes squarrosa</i> (Trin.) Keng	<i>Cls</i>	<i>PG</i>	3.82	0.73	0.70
<i>Cynanchum komarovii</i> Al.IIjin.	<i>Cyk</i>	<i>PF</i>	2.36	2.09	0.10
<i>Heteropappus altaicus</i> (Willd.) Novopokr.	<i>Hea</i>	<i>PF</i>	3.34	0.31	2.43
<i>Convolvulus ammannii</i> Desr.	<i>Coa</i>	<i>PF</i>	4.91	4.78	0.42
<i>Oxytropis aciphylla</i> Ledeb.	<i>Oxa</i>	<i>PS</i>	3.53	0.38	0.00
<i>Euphorbia humifusa</i> Willd.	<i>Euh</i>	<i>AF</i>	0.22	0.00	0.08
<i>Polygala tenuifolia</i> Willd.	<i>Pot</i>	<i>PF</i>	2.02	0.19	0.00
<i>Gueldenstaedtia stenophylla</i> Bge.	<i>Gus</i>	<i>PL</i>	0.85	0.45	0.00
<i>Leymus secalinus</i> (Georgi) Tzvel.	<i>Les</i>	<i>PG</i>	7.28	6.26	2.77
<i>Ixeris chinensis</i> (Thunb.) Nakai var. <i>graminifolia</i> (Ledeb.) H.C.Fu	<i>Icg</i>	<i>PF</i>	0.84	1.25	0.89
<i>Peganum nigellastrum</i> Bge.	<i>Pen</i>	<i>PF</i>	1.39	0.00	0.91
<i>Artemisia scoparia</i> Waldst. et Kit.	<i>Ars</i>	<i>AF</i>	5.73	2.73	6.12
<i>Pennisetum centrasiatikum</i> Tzvel.	<i>Pec</i>	<i>PG</i>	3.10	6.60	3.01
<i>Tribulus terrestris</i> L.	<i>Trt</i>	<i>AF</i>	0.08	0.00	0.00
<i>Oxytropis racemosa</i> Turcz.	<i>Oxr</i>	<i>PL</i>	1.12	2.61	1.93
<i>Scorzonera divaricata</i> Turcz.	<i>Scd</i>	<i>PF</i>	3.58	2.16	9.68
<i>Euphorbia esula</i> L.	<i>Eue</i>	<i>PF</i>	0.77	0.62	1.29
<i>Salsola collina</i> Pall.	<i>Sac</i>	<i>AF</i>	0.21	0.69	0.23
<i>Gypsophila davurica</i> Turcz. ex Fenzl var. <i>angustifolia</i> Fenzl	<i>Gyd</i>	<i>PF</i>	0.16	0.00	0.00
<i>Astragalus scaberrimus</i> Bge.	<i>Ass</i>	<i>PL</i>	0.23	0.00	0.00
<i>Coryspermum tylocarpum</i> Hance	<i>Cot</i>	<i>AF</i>	0.34	1.08	0.94
<i>Echinops gmelini</i> Turcz.	<i>Ecg</i>	<i>AF</i>	0.17	0.00	0.30
<i>Glycyrrhiza uralensis</i> Fisch.	<i>Glu</i>	<i>PL</i>	0.33	1.58	2.44
<i>Allium mongolicum</i> Regel	<i>Alm</i>	<i>PF</i>	0.71	0.00	0.00
<i>Olgaea leucophylla</i> (Turcz.) Iljin	<i>Oll</i>	<i>PF</i>	0.09	0.00	0.00
<i>Iris tenuifolia</i> Pall.	<i>Irt</i>	<i>PF</i>	0.17	0.20	0.00
<i>Echinops latifolius</i> Tausch.	<i>Ecl</i>	<i>PF</i>	0.00	0.60	0.73

LPC *L. potaninii* (dominant) community, *LPC-AOC* the ecotone of *L. potaninii* (dominant) community and *A. ordosica* (dominant) community, *AOC* *A. ordosica* (dominant) community, *AF* annual forbs, *PF* perennial forbs, *PG* perennial grass, *PL* perennial legume, *PS* perennial semi-shrub. The abbreviations are the same below

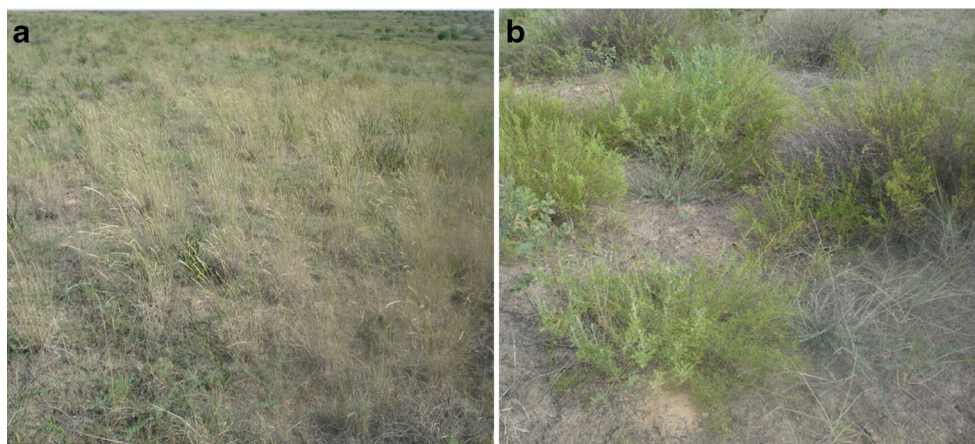
both 0–5- and 5–10-cm layers, using a 5-cm diameter soil auger in each 1 m×1-m quadrat. Soil samples at the same layer in each quadrat were then mixed to a pooled sample. A total of 180 mixed soil samples were gathered for soil chemical analyses. All the mixed samples were carefully labeled and taken to the laboratory for subsequent processing.

2.3 Laboratory analyses

In the laboratory, soil samples were laid open on plastic cloth and naturally air-dried. After drying, coarse gravel, rubble, and biotic residual were carefully picked out and discarded. Soil

samples were then sieved through a sifter with an aperture diameter of 1 mm and then blended. The samples were then divided into two parts. One part was used to analyze soil available nutrients, pH, and electrical conductivity (*EC*); the other was ground to sieve through another sifter with an aperture diameter of 0.15 mm and then used for the analyses of soil organic carbon (*SOC*) and total nitrogen (*TN*). *SOC* was analyzed using the potassium dichromate oxidation method, *TN* was analyzed with the Kjeldahl procedure, soil available phosphorus was measured by the 0.5 M NaHCO₃ method, soil available potassium was tested by flame photometry, and soil pH value and *EC* were analyzed in a 5:1 water-soil aqueous extract (ISSCAS 1978).

Fig. 2 Photos of the *L. potaninii* (dominant) community (a) and the ecotone (b)



2.4 Statistical analyses

The importance value (*IV*) of a given species in a quadrat was calculated as the average value of the relative values for this species, including relative abundance, relative height, relative

cover, and relative frequency. Relative abundance of this species in the quadrat is calculated with the following equation: (Eq. 1)

$$\text{Relative abundance} = \frac{\text{Abundance of this species}}{\text{Total abundance of all species}} \times 100 \tag{1}$$

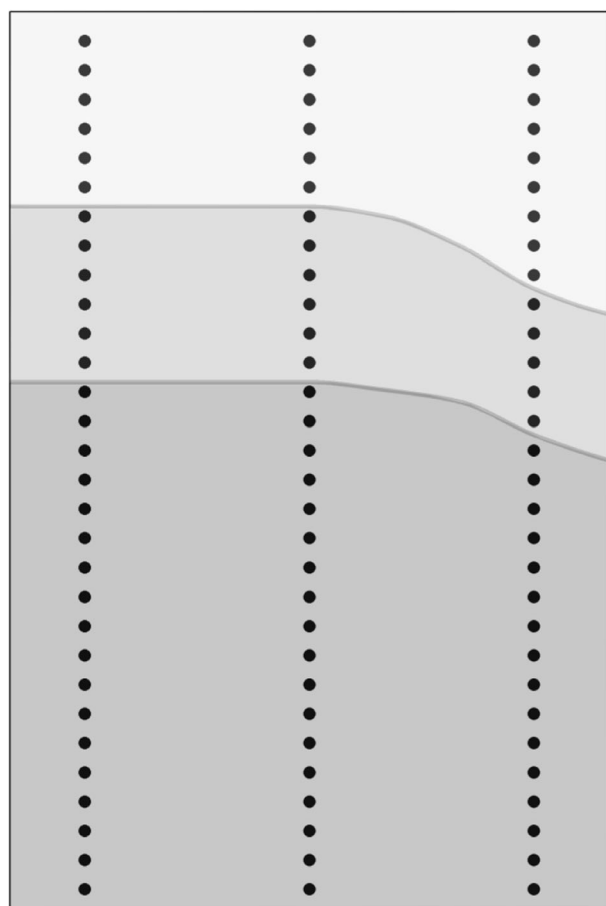


Fig. 3 Schematic diagram of sampling scheme in the study area

Relative height, relative cover, and relative frequency of this species were calculated in the same way (Myers and Bazely 2003). The *IVs* of other species were also calculated in this method. From our field observations, we found obvious changes of community composition along the transect, i.e., *A. ordosica* gradually replaced *L. potaninii* and some other herbaceous species to become the dominant species in the community. Nevertheless, we still applied the moving split-window techniques to quantify the width of the ecotone, using the species *IVs* in the ecotone determination processes (Shi et al. 2010). The principle of the moving split-window analysis is shown in Fig. 4. For the statistical analyses, we set a window including *w* sampling quadrats (*w* is an even number) and equally divided the whole window into two parts: A and B. The window included the first *w* quadrats of the first transect at the beginning. We calculated the dissimilarity between A and B using the squared Euclidean distance (SED) (Johnston et al. 1992; Choesin and Boerner 2002) (Eq. 2)

$$\text{SED}_{nw} = \sum_{i=1}^a (X_{iAw} - X_{iBw})^2 \tag{2}$$

where *n* is the sequence number of the sampling quadrat; *w* is the width of the window; *a* is the number of the variables sampled in every quadrat; X_{iAw} denotes the mean of variable

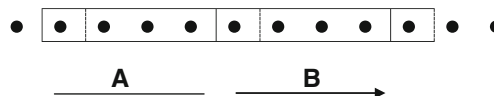


Fig. 4 Schematic diagram of the principle for the moving split-window analysis. Black circle sampling quadrat (Johnston et al. 1992). A, B The half windows of the whole window

i in half window A when the width of the window is w ; X_{iBw} denotes the mean of variable i in half window B when the width of the window is w . Then, we moved the whole window one quadrat ahead along the transect and calculated the SED between A and B again until the last sampling quadrat was included for calculation. A series of SED values representing the dissimilarity between A and B was produced in this process. We calculated SED in this way for other two transects and for the window width of 4, 6, 8, and 10, respectively. A figure for each transect was then drawn using the SED values against the sampling quadrats along the transect. The peak of the curve of the figure was regarded as the central location of the ecotone as the discontinuity of the transect happens at the maximum SED value. The width of the peak, i.e., the distance between the point where the curve of the figure, starts to go up in the left side of the peak and the point where it ended to go down in the right side of the peak is the width of the ecotone. We compared the results and found that when the window width is 4 or 6, the sample to sample noise was large and cannot get a clear determination of the ecotone; when the window width is 8 and 10, the location and width of the ecotone were almost the same. So, we adopted the results of the ecotone determination with the window width of 8 and 10. Based on these results, the ecotone in the first and second transects were both from quadrat 19 to 24; the ecotone in the third transect was from quadrat 17 to 21 (Fig. 3) (Shi et al. 2010).

The whole study site was divided into three different habitats based on the ecotone determination mentioned above, i.e., *L. potaninii* (dominant) community site, the ecotone, and *A. ordosica* (dominant) community site. Vegetation characteristics and soil chemical properties in this study were classified into these three habitats in order to determine how they change along the total ecotone. The geostatistical analyses were conducted taking the study site as a whole without community classification, because geostatistical analysis can reveal the changes in the whole site and also provide detailed information about how each variable evolves along the transect. Three models (spherical, exponential, and linear) were determined to be the best choice for the analyzed variables. Species richness was defined as the number of species in each 1 m × 1-m quadrat; species diversity was calculated with the Shannon-Wiener Index (H), based on species abundance. Species evenness was determined with the Pielou Index (Gilliam and Dick 2010).

All data were preliminarily processed with Microsoft Office Excel 2003, in which statistic items, such as mean, standard deviation, median, maximum, minimum, coefficient of variance (CV), and species IVs , were calculated. Other statistical processes including a normality test of data distribution (Kolmogorov-Smirnov test), correlation analysis, regression analysis, least significant difference (LSD) test (where equal variance is assumed), and Tamhane's T2 test (where equal variance is not assumed) were carried out with SPSS (version

13.0). The method of stepwise regression was applied for the multiple regression analysis. Outliers were detected and removed before the regression analysis to control the quality of the regression model. Significant differences between different communities (LPC , the ecotone, and AOC) were at a $P < 0.05$ level. The data were processed with a logarithmic transformation if they were not in accordance with a normal distribution in the $K-S$ test. Geostatistical analyses were carried out with the GS^+ software (version 5.1; Gamma Design Software, Plainwell, Michigan) for the SV calculation, best model choice, and Kriging interpolation. SV is a regression model of values of semi-variances ($\gamma(h)$) calculated with the following formula (Wang et al. 2007): (Eq. 3)

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \quad (3)$$

where $N(h)$ is the total amount of sample pairs with a separation of lag distance h ; $Z(x_i)$ and $Z(x_i + h)$ are the measured values at the location x_i and $x_i + h$, respectively. GS^+ 5.1 chose the best model for each variable according to its data set. In our study, we focused on isotropic SVs because no significant directional patterns were found when comparing isotropic and corresponding anisotropic SVs at 0° , 45° , 90° , and 135° (Wang et al. 2007; Li et al. 2009). Four important parameters were used in this study to analyze SVs : nugget variance (Co), sill ($Co + C$), relative structural variance $C / (Co + C)$, and range (A). The nugget variance is either the random error or the spatial variation existing on a finer scale than the minimum analyzed scale (Isaaks and Srivastava 1989; Schlesinger et al. 1996). The sill is the total variation, including nugget variance (Co) and structural variance (C) (Cressie 1993). $C / (Co + C)$ is a useful index measuring the magnitude of spatial dependence in an analyzed variable, and range (A) is the spatial scale on which the spatial dependence is expressed. Either a small value of range or no detected spatial dependence indicates that the variable has a homogeneous distribution on the measured scale (Gross et al. 1995). Only samples within the distance of range (A) are correlated, or otherwise considered independent (Li et al. 2009). Based on the SV analyses, the Kriging interpolation was used to show in detail the changes of soil chemical properties along the ecotone. Ordinary block Kriging was used for generating maps with the program GS^+ (Jackson and Caldwell 1993b).

3 Results

3.1 Changes of vegetation and soil properties along the ecotone

Plant community composition changed along the ecotone, from the LPC to the AOC (Table 1). Almost all plant species

(31) encountered in this study site could be found in the *LPC*. However, good quality forage grasses such as *A. mongolicum* and *S. bungeana*, with *IVs* as high as 13.94 and 9.05, respectively, disappeared in the *AOC*. Changes of *IVs* along the ecotone were also caused (mainly) by the development of *A. ordosica*, whose *IV* changed dramatically from 5.30 in the *LPC* to 30.71 in the ecotone, and lastly to 36.45 in the *AOC*.

Entire data sets and subsets for variables analyzed in this study all fitted a normal distribution except for the *LPC* subset of the pH at 5–10-cm depth, and the entire data set of available P and pH both at 5–10-cm depth (Table 2). We processed the data of these three sets with a logarithmic transformation. All these three data sets fitted a normal distribution after transformation. The data set of species richness, diversity, and evenness all exhibited a high central tendency with close mean and median values (Table 3). The coefficient of variance (*CV*) for vegetation variables showed that all of them shared a moderate data variation along the ecotone, with *CV* values more than 0.1 but less than 1.0.

There was a significant difference ($P < 0.05$) in the values of soil organic C (*SOC*), total N (*TN*), available K (*AK*), and electrical conductivity (*EC*) between the *LPC* and the *AOC* at both soil layers (Table 4). Significant differences between the ecotone and the *LPC* were seen in the following averaged values: *SOC* (0–5-cm); *AK* (0–5 and 5–10-cm). Between the ecotone and the *AOC*, significant differences were seen in the averaged *SOC* and *EC* values both at 5–10-cm. However, there were no significant differences between the ecotone and the *AOC* observed in the values of *AP* and pH at both layers. All values of *SOC*, *TN*, *AP*, and *EC* at both layers decreased along the ecotone, from the *LPC* to the *AOC*, while the value of *AK* at 0–5-cm decreased significantly ($P < 0.05$) from the *LPC* to the ecotone, and then increased slightly from the ecotone to the *AOC*. All the results showed that soil nutrient content diminished along the ecotone from the *LPC* to the *AOC* in general.

Table 3 Descriptive statistics of vegetation characteristics along the ecotone of *L. potaninii* (dominant) community and *A. ordosica* (dominant) community in Southern Mu Us Sandy Land, China

Variable	Mean	SD	Median	Max.	Min.	<i>CV</i>
Species richness	9.01	3.00	9	14	3	0.33
Species diversity	1.68	0.38	1.70	2.44	0.83	0.22
Species evenness	0.79	0.11	0.80	0.97	0.39	0.14

3.2 Geostatistical analyses of soil and vegetation variables

The *SVs* and their parameters for soil and vegetation variables are shown in Table 5. The spherical model is the best for both *SOC* and pH at 5–10-cm, *EC* at 0–5-cm, and species diversity. The exponential model is the best for *SOC* at 0–5-cm and *EC* at 5–10-cm. The linear model is the best for pH at 0–5-cm and species evenness, both of which had very low relative structural variances (0.002 and <0.001 , respectively). This suggested that no spatial structural variances exist within either of these data sets (Fig. 5c, h). However, the values of $C/(C_0+C)$ for *SOC*, *EC* at both layers, pH at 5–10-cm, and species diversity, were relatively large, all being over 0.500 (Table 5), and showed relatively strong spatial autocorrelations within the ranges (*A*), changing from 20.40 m (pH at 5–10-cm) to 510.9 m (*EC* at 5–10-cm). All analyzed soil variables had larger spatial structural variances at 5–10-cm than those at 0–5-cm, indicating that *SOC*, pH, and *EC* at subsurface (5–10-cm) soil layers were better autocorrelated than those at surface (0–5-cm) soil layers. The ranges (*A*) of *SOC* and *EC* showed the same trend (Fig. 5a, b, e, f).

Results of cross-validation showed that the regression coefficients of soil chemical properties were close to 1.0 in general (Table 6), indicating that the values estimated via Kriging fitted well with the actual values (Gamma Design Software 2001). The standard errors of the regression coefficients were small, and so, the standard deviations of the underlying errors were small and the ordinary least square estimations performed well.

Table 2 Significant values (two-tailed) of *K-S* test for normality checking of the data along the ecotone of *L. potaninii* (dominant) community and *A. ordosica* (dominant) community in Southern Mu Us Sandy Land, China

Data set	<i>S</i>	<i>H'</i>	<i>J</i>	<i>TN1</i>	<i>TN2</i>	<i>AK1</i>	<i>AK2</i>	<i>AP1</i>	<i>AP2</i>	<i>SOC1</i>	<i>SOC2</i>	pH1	pH2	<i>EC1</i>	<i>EC2</i>
<i>LPC</i>	0.139	0.154	0.506	0.889	0.597	0.570	0.797	0.123	0.067	0.772	0.951	0.404	0.031	0.709	0.372
<i>LPC-AOC</i>	0.984	0.944	0.962	0.918	0.993	0.687	0.729	0.839	0.665	0.961	0.765	0.933	0.933	0.881	0.541
<i>AOC</i>	0.573	0.985	0.762	0.582	0.266	0.381	0.677	0.870	0.487	0.935	0.952	0.575	0.760	0.371	0.806
Entire set	0.083	0.515	0.188	0.327	0.371	0.549	0.443	0.056	0.023	0.441	0.972	0.492	0.030	0.306	0.533

S species richness, *H'* species diversity, *J* species evenness, *TN* total nitrogen: *TN1* 0–5-cm, *TN2* 5–10-cm, *OC* organic carbon: *OC1* 0–5-cm, *OC2* 5–10-cm, *AP* available phosphorus: *AP1* 0–5-cm, *AP2* 5–10-cm, *AK* available potassium: *AK1* 0–5-cm, *AK2* 5–10-cm, *EC* electrical conductivity: *EC1* 0–5-cm, *EC2* 5–10-cm. The abbreviations are the same below

Table 4 Soil attributes along the ecotone of *L. potaninii* community and *A. ordosica* community in Southern Mu Us Sandy Land, China, (*n*=90 for both soil layers)

Variable	Soil layer (cm)	LPC	LPC-AOC	AOC
Soil total N (g/kg)	0–5	0.17±0.06a	0.15±0.07ab	0.14±0.06b
	5–10	0.20±0.10a	0.18±0.08ab	0.14±0.08b
Organic C (g/kg)	0–5	4.10±0.95a	3.47±1.23bc	3.44±1.17c
	5–10	4.48±1.55a	4.18±1.49a	2.99±1.43b
Available P (mg/kg)	0–5	4.49±1.89a	3.96±1.28a	3.67±1.28a
	5–10	2.43±1.40a	2.07±0.50a	1.87±1.18a
Available K (mg/kg)	0–5	106.41±40.96a	68.76±35.41bc	74.82±35.36c
	5–10	88.79±42.46a	52.96±25.78bc	48.95±22.47c
pH	0–5	8.86±0.09a	8.87±0.07a	8.88±0.07a
	5–10	8.86±0.12a	8.88±0.07a	8.91±0.06a
EC (µs/cm)	0–5	81.93±12.52a	79.06±12.61ab	74.00±10.08b
	5–10	82.06±10.29a	81.94±12.33a	72.26±10.09b

Values are shown in Mean±SD

LPC *L. potaninii* (dominant) community, LPC-AOC the ecotone of *L. potaninii* (dominant) community and *A. ordosica* (dominant) community, AOC *A. ordosica* (dominant) community

Values containing the same letter indicate no significant differences among different community types at *P*<0.05 level

The Kriging interpolation maps showed detailed information of soil chemical properties changing along the ecotone, with patches of different values of soil properties distributed along the transect (Fig. 6). The changes in SOC along the ecotone at the two layers were the same, with the highest SOC concentrations in the LPC, relatively low concentrations in the ecotone, and the lowest in the AOC (Fig. 6a, b). EC at both layers showed a similar spatial variation with SOC (Fig. 6e, f). The highest pH values were found at 0–5-cm, distributed in the ecotone, with the lowest values found in the LPC (Fig. 6c). However, similarities in pH values at 5–10-cm were found between the ecotone and the AOC, and these were relatively high compared to those found in the LPC (Fig. 6d).

3.3 Soil-vegetation relationships

For soil properties, significant correlations were found mainly among SOC, TN, and EC. There were positively

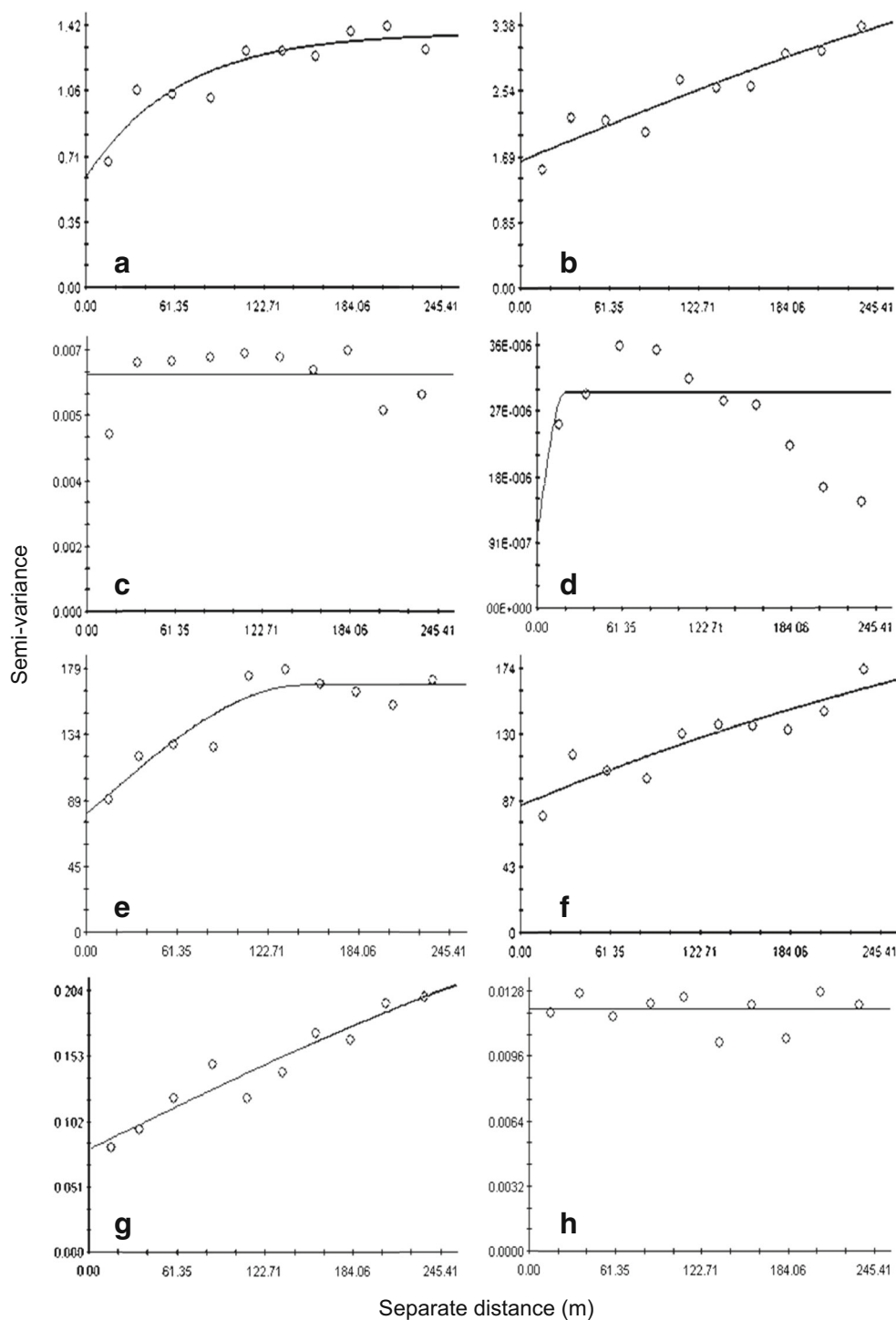
significant correlations between all of the following variables: TN (0–5-cm), TN (5–10-cm), SOC (0–5-cm), SOC (5–10-cm), EC (0–5-cm), and EC (5–10-cm) (*P*<0.05) (Table 7). In addition, positively significant correlations were also found between AP (0–5-cm), AP (5–10-cm), AK (0–5-cm), and AK (5–10-cm) (*P*<0.05), indicating that there were positive relationships between soil available nutrients along the ecotone. For vegetation characteristics, species richness was positively correlated with TN (0–5-cm), TN (5–10-cm), SOC (0–5-cm), SOC (5–10-cm), EC (0–5-cm), and EC (5–10-cm) (*P*<0.05). At the same time, species diversity was positively correlated with TN (0–5-cm) and SOC (0–5-cm) (*P*<0.05), and negatively correlated with pH (0–5-cm) (*P*<0.05). All these results indicate that SOC, TN, EC, and pH could be important soil factors associated with vegetation distribution along the community ecotone in the sandy grassland.

Tables 8 and 9 show the results of stepwise regression analyses between plant species richness and soil

Table 5 Analyses of the spatial structure for soil and vegetation variables along the ecotone of *L. potaninii* (dominant) community and *A. ordosica* (dominant) community in Southern Mu Us Sandy Land, China

Variable	Soil layer (cm)	Model	Co	Co+C	C/(Co+C)	A(m)	r ²
SOC (g/kg)	0–5	Exponential	0.597	1.378	0.567	194.100	0.851
	5–10	Spherical	1.633	4.152	0.607	492.60	0.884
pH	0–5	Linear	0.007	0.007	0.002	233.72	0.000
	5–10	Spherical	0.00001	0.00003	0.612	20.400	0.005
EC (µs/cm)	0–5	Spherical	79.70	167.60	0.524	148.20	0.861
	5–10	Exponential	83.60	292.70	0.714	510.90	0.808
Species diversity		Spherical	0.080	0.262	0.695	496.00	0.914
Species evenness		Linear	0.012	0.012	0.000	233.61	0.006

Fig. 5 Semivariograms of SOC at 0–5-cm (a), 5–10-cm (b), soil pH at 0–5-cm (c), 5–10-cm (d), soil EC at 0–5-cm (e), 5–10-cm (f), species diversity (g), and species evenness (h) along the ecotone of *L. potaninii* (dominant) community and *A. ordosica* (dominant) community in Southern Mu Us Sandy Land, China



properties, and between plant species diversity and soil properties. The stepwise regression analyses selected soil total nitrogen at 0–5-cm (*TN1*), soil electrical conductivity at 0–5-cm (*EC1*), and soil available potassium at 5–10-cm (*AK2*) from all soil properties measured in this study as the predictors for plant species richness. For plant species diversity, only *TN1* was selected. The models of plant species richness and diversity

can be expressed as the following equations: (Eqs. 4 and 5)

$$y_1 = 0.234 + 17.386x_1 + 0.063x_2 + 0.011x_3 \quad (4)$$

$$t = (0.167) (4.631) (3.484) (2.104)$$

$$R^2 = 0.525 \quad DW = 1.663$$

Table 6 Cross-validation analysis of soil and vegetation variables along the ecotone of *L. potaninii* (dominant) community and *A. ordosica* (dominant) community in Southern Mu Us Sandy Land, China

Variable	Soil layer (cm)	Regression coefficient	Standard error	y intercept
SOC (g/kg)	0–5	1.021	0.157	-0.074
	5–10	1.000	0.201	0.015
pH	0–5	0.949	0.426	0.457
	5–10	0.505	0.256	0.470
EC (μs/cm)	0–5	0.928	0.172	5.791
	5–10	0.990	0.208	1.003

where y_1 is the plant species richness; x_1 is the *TN1*; x_2 is the *EC1*; x_3 is the *AK2*; t is the value of the t-statistic; R^2 is the coefficient of determination; DW is the value of Durbin-Watson statistic.

$$y_2 = 1.450 + 1.64x_1 \tag{5}$$

$$t = (14.763)(2.899)$$

$$R^2 = 0.129 \quad DW = 1.170$$

where y_2 is the plant species diversity; x_1 , t , R^2 , and DW represent the same meanings as those in Eq. 4.

DW in Eq. 4 was found to be between the lower limit d_L and the upper limit d_U by checking the Durbin-Watson Table. In this case, it is impossible to know whether there is first-order autocorrelation between residuals or not. DW in Eq. 5 was less than the lower limit d_L , and so, there was first-order autocorrelation between residuals. Further autocorrelation diagnostics were conducted in EViews software with correlogram Q-statistics and serial correlation LM test. Results showed that there was no first-order or high-order autocorrelation between residuals in Eq. 4; there was first-order and 14-order autocorrelation between residuals in Eq. 5. Equation 5 was therefore modified with generalized difference method in EViews to eliminate the autocorrelations between residuals. The modified model is shown as follows: (Eq. 6)

$$y'_2 = 1.418 + 1.687x_1 \tag{6}$$

$$t = (15.699) (3.455)$$

$$R^2 = 0.458 \quad DW = 1.910$$

$$AR(1) = 0.525, \quad AR(14) = -0.235$$

$$t = (4.337) (-2.163)$$

where y'_2 is the plant species diversity; $AR(1)$ and $AR(14)$ are the estimated values of the coefficient for first- and 14-order autocorrelation, respectively; x_1 , t , R^2 , and DW represent the same meanings as those in Eq. 4. The second t is the value of t-statistics of $AR(1)$ and $AR(14)$.

DW in Eq. 6 is between d_U and 2.0, indicating that there was no first-order autocorrelation between residuals. No high-order autocorrelation was found in further autocorrelation diagnostics for Eq. 6.

The test of normality and homoscedasticity are shown in Figs. 7 and 8, respectively. The histograms show that both two groups of residuals are normal. The scatter plots show that almost all standardized predicted values distributed randomly within the value of ± 2 of standardized residual, suggesting that residuals in both groups fulfill the hypothesis of homoscedasticity. Collinearity statistics showed that the values of tolerance for *TN1*, *EC1*, and *AK2* were all more than 8.50, and the variance inflation factors (*VIF*) for these three variables were all very close to 1.0 (Table 8), indicating that there is no collinearity among these three independent variables.

4 Discussion

4.1 Spatial heterogeneity of soil and vegetation variables

The spatial heterogeneity of soil properties has been recognized as a common characteristic of terrestrial ecosystems and is often associated with different effects on vegetation patterns (Fransen et al. 2001; Buxbaum and Vanderbilt 2007; Franz et al. 2011). However, in previous studies, soil spatial heterogeneity was commonly assumed to be horizontal heterogeneity, i.e., soil heterogeneity across a given area at a certain layer, e.g., 0–10-cm. This kind of heterogeneity does not include spatial heterogeneity at any other soil layers. However, the spatial heterogeneity of another soil layer may have an important effect on plant competition and vegetation attributes due to the differences of the depth of root distribution for different plants. Therefore, there is a need to study the horizontal spatial heterogeneity of soil properties at different layers.

In this study, soil properties at different layers had different best *SV* models which had different parameters, including C_o , C_o+C , $C/(C_o+C)$, and A . Similar results were found at different soil layers for soil water content in Horqin Sandy Land (Zuo et al. 2009b; Ma et al. 2011), and for soil available nitrogen forms within each community in Michigan (Gross et al. 1995). Similar studies in the past seemed to focus mainly on soil water and nitrogen. The *SV* parameters of other soil properties including *SOC*, *pH*, and *EC* in this study also showed changes between different soil layers. Based on our results, it can be said that there is a delaminated phenomenon for the spatial heterogeneity of *SOC*, *pH*, and *EC*, i.e., the

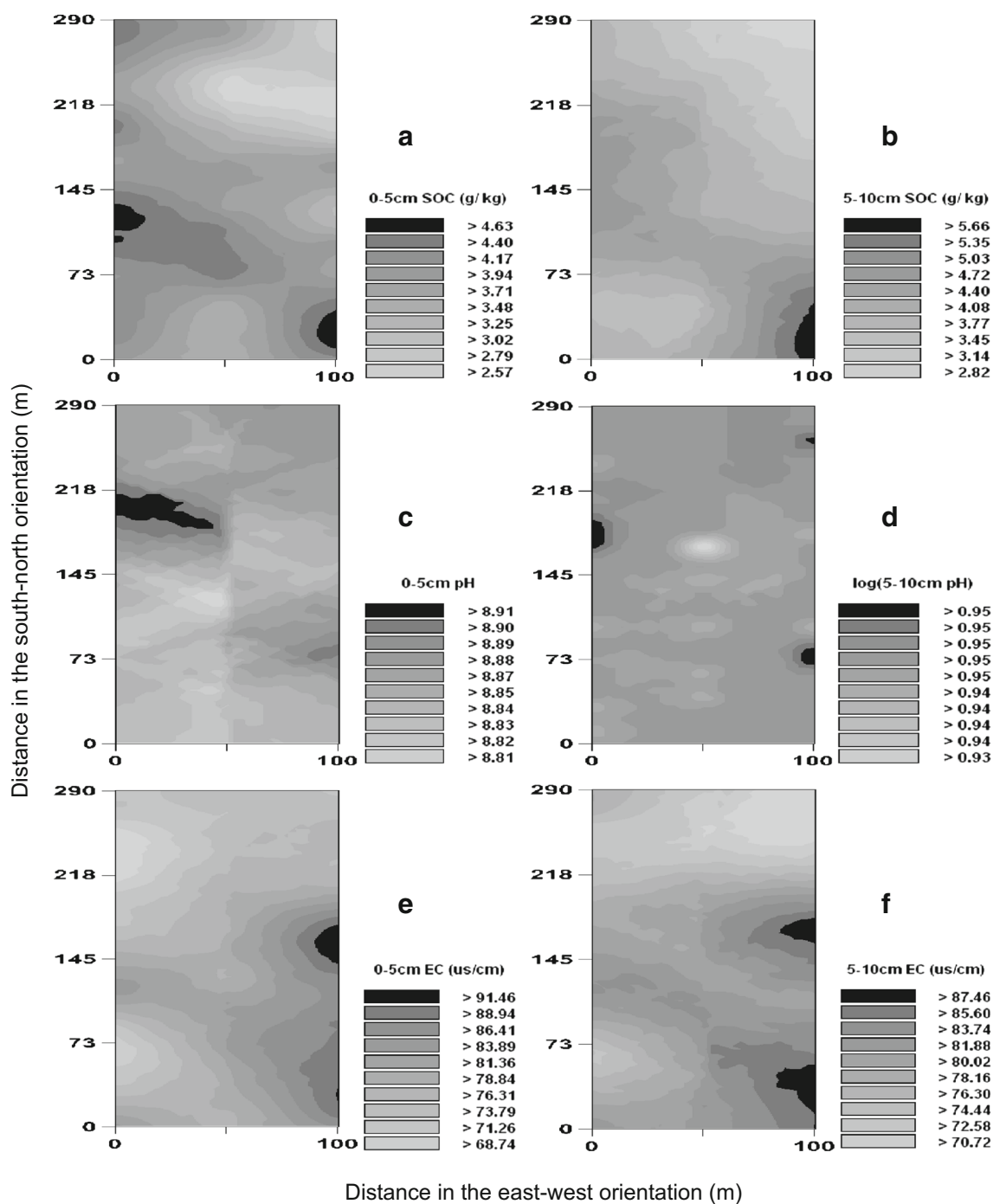


Fig. 6 Spatial distribution of *SOC* at 0–5-cm (a), 5–10-cm (b), soil pH at 0–5-cm (c), 5–10-cm (d), and soil *EC* at 0–5-cm (e), 5–10-cm (f) along the ecotone of *L. potaninii* (dominant) community and *A. ordosica* (dominant) community in Southern Mu Us Sandy Land, China

horizontal features of spatial heterogeneity of *SOC*, pH, and *EC* changed at different soil layers. Combined with the previous studies, we assume that the delamination of the spatial heterogeneity is a common phenomenon for soil properties. An experimental design including more soil layers and properties in different ecosystems would be necessary in order to verify this assumption and to show its ecological effects on plants.

The *SV* parameters in this study were larger at 5–10-cm than those at 0–5-cm for *SOC* and *EC*, indicating an increase of spatial variability for *SOC* and *EC* in the subsurface soil. This is in accordance with the results reported by Zuo et al. (2009b), in which a general increase of *Co* and *Co+C* was found with the increasing soil depth, whereas Gross et al. (1995) showed that there was a decrease of *Co* and *Co+C* with the increase in soil depth. This contradiction may be due to the regional variations

Table 7 Spearman’s rank correlation matrix for soil properties and vegetation characteristics along the ecotone of *L. potaninii* (dominant) community and *A. ordosica* (dominant) community in Southern Mu Us Sandy Land, China

	TN1	TN2	OC1	OC2	AP1	AP2	AK1	AK2	pH1	pH2	EC1	EC2	S	H'	J
TN1	1														
TN2	0.63**	1													
OC1	0.44**	0.32**	1												
OC2	0.51**	0.65**	0.51**	1											
AP1	-0.08	-0.12	0.08	0.03	1										
AP2	0.07	0.06	0.07	0.08	0.26*	1									
AK1	-0.03	0.11	0.10	0.10	0.40**	0.32**	1								
AK2	-0.10	0.01	-0.06	0.00	0.38**	0.35**	0.78**	1							
pH1	0.10	0.19	-0.26*	0.09	-0.13	-0.01	-0.20	-0.15	1						
pH2	0.07	0.09	-0.24*	0.01	0.03	0.19	-0.15	-0.04	0.53**	1					
EC1	0.37**	0.37**	0.26*	0.30**	-0.22*	-0.02	0.01	0.07	-0.18	-0.17	1				
EC2	0.49**	0.61**	0.36**	0.52**	-0.12	0.02	0.05	0.01	-0.10	-0.22*	0.68**	1			
S	0.36**	0.27*	0.28*	0.27*	-0.17	0.07	0.10	0.13	-0.10	-0.14	0.34**	0.30**	1		
H'	0.26*	0.14	0.23*	0.12	-0.07	0.09	0.09	0.10	-0.22*	-0.09	0.15	0.21	0.71**	1	
J	-0.02	-0.05	0.02	-0.13	0.08	-0.06	0.03	-0.01	-0.18	0.07	-0.03	-0.02	-0.00	0.61**	1

* $P < 0.05$, ** $P < 0.01$ (two-tailed)

of the study sites. Another study carried out on the southern edge of the Tengger Desert, China (Ma et al. 2011), showed similar results to ours, with an increase of $Co+C$ with increasing soil depth, suggesting a rise in the total variability of soil water with rising soil depth. Moreover, the study site of ours and that of Zuo et al. (2009b) were located in Southern Mu Us Sandy Land and Horqin Sandy Land, respectively. These three studies with similar results were all located in desert or sandy land, which is characterized by wind erosion that can affect the litter redistribution on the soil surface and may affect soil nutrient and water cycling, leading to more homogeneity in the surface soil and more variability in the subsurface soil. The study sites of

Gross et al. (1995) were not located in desert or sandy land, but in field and forest, which probably explains the difference in their results from those of our study.

The Co and $Co+C$ of soil pH in this study did not have the changing regularity mentioned above, but both parameters were very low, suggesting that soil pH did not vary much along the $LPC-AOC$ ecotone at both the surface and subsurface soil layers. In previous studies, linear models were also found for soil pH (Dick and Gilliam 2007) and some other soil properties, such as available N (Gross et al. 1995; Gilliam and Dick 2010), mineralization and nitrification (Jackson and Caldwell 1993b), and soil mechanical compositions (Zuo et al. 2009b). The linear SV

Table 8 Coefficients of models produced during the regression analysis between species richness and soil properties

Model	Unstandardized coefficients		Standardized coefficients	t	Sig.	Collinearity statistics				
	B	Std. Error				Tolerance	VIF			
1	(Constant)	5.341	.704	7.589	0.000	1.000	1.000			
	TN1	21.336	3.947					0.600	5.405	0.000
2	(Constant)	1.001	1.400	0.715	0.478	0.866	1.155			
	TN1	16.426	3.849					0.462	4.267	0.000
	EC1	0.065	0.019					0.377	3.484	0.001
3	(Constant)	0.234	1.403	0.167	0.868	0.853	1.172			
	TN1	17.386	3.754					0.489	4.631	0.000
	EC1	0.063	0.018					0.365	3.484	0.001
	AK2	0.011	0.005					0.207	2.104	0.040

B the coefficients of partial correlation; t value of the hypothesis test that partial correlation and the constant are 0; $Sig.$ the significant value of the hypothesis test that partial correlation and the constant are 0; VIF the variance inflation factor. The abbreviations are the same below

Table 9 Coefficients of the model produced during the regression analysis between species diversity and soil properties

Model		Unstandardized coefficients		Standardized coefficients	t	Sig.	Collinearity statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	1.450	0.098		14.763	0.000		
	TN1	1.642	0.566	0.358	2.899	0.005	1.000	1.000

model was regarded as an indication of a lack of significant spatial dependence in some studies (Jackson and Caldwell 1993b; Zuo et al. 2009b), and the relevant variable being calculated seemed to be random (Schlesinger et al. 1996). In some other studies, however, linear models were taken as a response to one of three spatial patterns, i.e., a linear pattern, for the calculated variable (Dick and Gilliam 2007; Gilliam and Dick 2010), and may still have comparatively large spatial dependences (Augustine and Frank 2001; Gross et al. 1995). Soil pH at 0–5-cm and species evenness in this study were both best fit for linear SV , with no spatial dependences found in these two variables (very low value of $C / (Co+C)$). This result suggests that our sampling scale, i.e., 10 m, may have been too large to obtain solid spatial dependence for soil pH at 0–5-cm and species evenness (Allen and Hoekstra 1991; Jackson and Caldwell 1993b). Strong spatial autocorrelation may exist for them on finer scales. A more intensive sampling scheme would help to further detect the spatial heterogeneity of pH at 0–5-cm and species evenness.

$C/(Co+C)$ is the relative structural variance, and an important index in semivariance analyses (Gross et al. 1995). Its value is also taken as the magnitude of spatial heterogeneity (Zhou et al. 2008). The $C/(Co+C)$ of all soil variables calculated in this study were larger at 5–10-cm than those at 0–5-cm, indicating a stronger spatial autocorrelation in the subsurface soil. Based on this result, we believe that subsurface soil properties have a larger spatial heterogeneity than those of surface soil. Plant diversity was found to be significantly related to soil spatial heterogeneity in many studies (e.g. Dick and Gilliam

2007). The spatial heterogeneity in subsurface soil in this study is more closely related to species diversity than that in surface soil. The soil heterogeneity at the second layer is therefore preferred for explaining plant species diversity in this study.

The method of Kriging applied in this study is Block Kriging and belongs to Ordinary Kriging. The Ordinary Kriging is a widely used Kriging method applying in soil mapping. There is no requirement to know the mean, and it can be evaluated from the input data when the Ordinary Kriging is applied (Bezzi and Vitti 2005). Regression Kriging is an alternative Kriging method for soil mapping. Zhu and Lin (2010) found that the Regression Kriging is more accurate than the Ordinary Kriging in interpolating soil properties, when point-based observations cannot well obtain the spatial structure of the variable. Otherwise, the Ordinary Kriging is better for interpolating. Results in our study showed that relative structural variances for most variables are more than 0.5, indicating a good acquirement of the spatial structure by point-based observations. The Ordinary Kriging is therefore the better method for this study. Eldeiry and Garcia (2010) also found a better performance of the Ordinary Kriging than the Regression Kriging in generating accurate soil salinity maps. GS^+ software used in this study provides alternative Kriging methods, i.e., Point Kriging and Block Kriging. Compared to Point Kriging, the Ordinary Kriging has many advantages, such as improvements in the estimation variance and getting smoother maps (Trangmar et al. 1985). Geostatistical methods applied in this study are therefore the

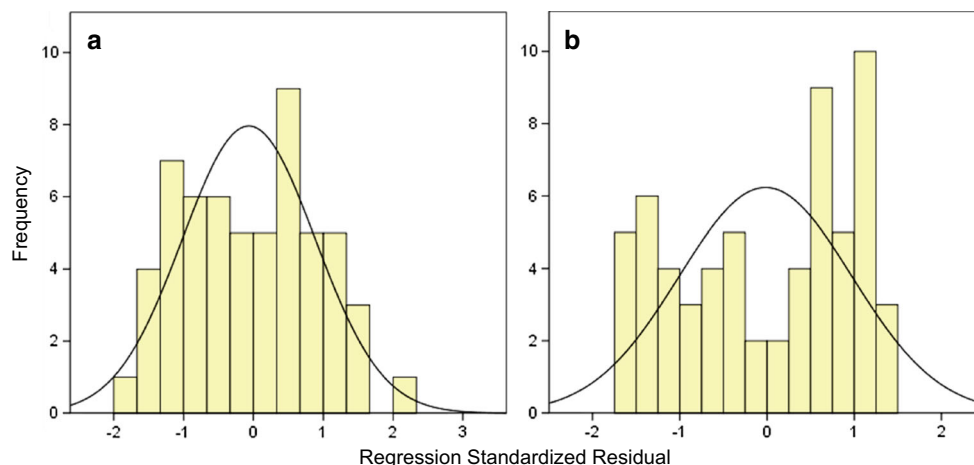
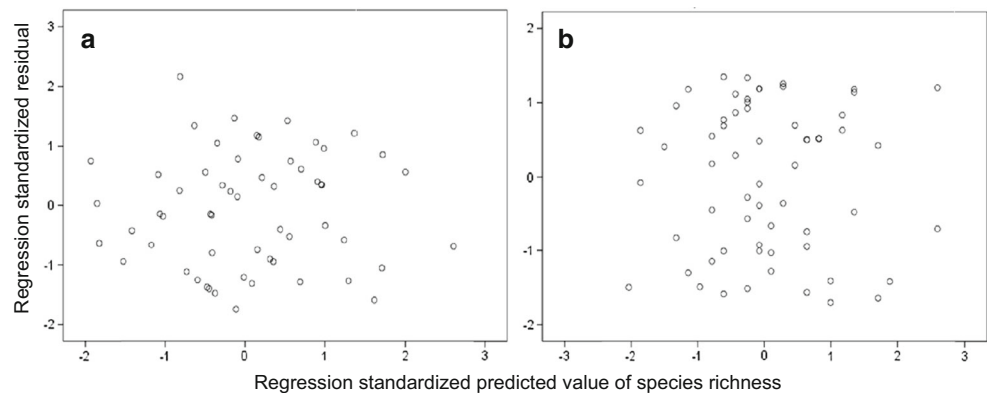
Fig. 7 Histograms of normality test for regression standardized residual in the multiple regression analyses between plant species richness and soil properties (a), and between plant species diversity and soil properties (b)

Fig. 8 Scatter plots of standardized predicted value and standardized residual in the multiple regression analyses between plant species richness and soil properties (a), and between plant species diversity and soil properties (b)



best choice and are suitable to the data in this study. Nevertheless, a systematic study on comparing different geostatistical methods would be useful to confirm this.

4.2 Vegetation succession, soil variation, and their relationships

The spatial process of retrogressive succession of plant community along the ecotone has been characterized by two different factors: the population and size changes of *A. ordosica* and the changes in vegetation composition in the study site. The latter, in turn, were indicated by species important values. This spatial process may be caused by the changes of soil properties and plant species competition, and even the combined ecological effects of soil and vegetation. Soil and vegetation are thought to interact normally with each other under all kinds of environmental conditions (Martinez-Fernandez et al. 1995; El-Ghani and Amer 2003).

The competition between plant species was most apparent between *A. ordosica* and grass species in the spatial process along the ecotone. It was probably brought about by spatial heterogeneity in soil chemical properties (Hutchings et al. 2003). The results of this study suggest a significant reduction in the values associated with the soil properties from the *LPC* to the *AOC*, which may have led to an intensification of the plant species competition. The habitat in the *AOC* was probably no longer suitable for some grass species, with the development of species competition along the ecotone. The semishrub *A. ordosica* adapted well to this low nutrient habitat and might have easily formed nutrient islands under its canopy, which fostered their existence. This supports the theory that fertility islands develop under shrubs in desert regions (Schlesinger et al. 1996; Li et al. 2008).

A. ordosica replaced *L. potaninii* gradually from the *LPC* to the *AOC* to become the dominant plant species in the *AOC*, indicating an increase of soil desertification along the ecotone (*A. ordosica* normally replaces other species to be the dominant species when soil desertification aggravates). Soil desertification was also indicated by the disappearance of some good quality forage grass species. These results are consistent

with a study carried out in Northern China, where a bunchgrass community and a sandy species community were identified as the first and last stages of a vegetation succession, respectively, with the development of soil desertification (Huang et al. 2007). Correlation and regression analyses between soil and plant may provide us with further information about the relationships between soil and vegetation in the process of vegetation succession.

Plant species richness and diversity were both positively correlated with surface *SOC* and *TN* ($P < 0.05$), suggesting that *SOC* and *TN* were intimately related to the plant community structure in the sandy grassland. Consistent with this model are the relationships between vegetation characteristics and soil C and N in several studies (Solon et al. 2012; El-Ghani and Amer 2003; Gross et al. 1995; Zuo et al. 2009a). All these studies show the great significance of soil C and N in determining plant community structure. This is attributed to the importance of soil C and N in determining decomposition, production, and nutrient redistribution for semiarid ecosystems (Law et al. 2012). In contrast to previous studies, vegetation succession was related to the variation of soil nutrients, which declined in general from the *LPC* to the *AOC*. However, it seems that there was an increase of soil nutrients accompanied with vegetation succession in some previous studies (Mitchell et al. 1997; Klinger 1996; Liang et al. 2010). This discrepancy is due to the fact that the vegetation succession in this study was a retrogressive succession, unlike that of Mitchell et al. (1997) and Liang et al. (2010). For Klinger (1996), the study site was on an island where bog may have higher soil histosol development than forest due to the effect of bryophyte.

Despite these discrepancies, the changes of soil nutrients should have significant effects on the spatial process of vegetation succession. A different plant community is likely to be generated by any increase of soil resources (Heil and Diemont 1983; Aerts and Berendse 1988; Van Der Eerden et al. 1991). A promotion of the process for vegetation succession by the development of soil nutrients was also shown by Klinger (1996) (histosol development), Zhu et al. (2012) (*SOC* accumulation), and Sparrius and Kooijman (2013) (soil nitrogen

availability increase). Soil nutrients, especially soil carbon and nitrogen, may control the direction and process of vegetation succession, due to their mediation in the soil biogeochemical processes.

Species richness was also positively correlated with *EC* at both layers in this study ($P < 0.01$), indicating that *EC* may be another factor affecting species richness. Significantly positive correlations between plant species richness and *EC* were also reported in several relevant studies (Zuo et al. 2009b; Fattahi and Ildoromi 2011; Gomaa 2012; Hájková and Hájek 2003). *EC* (along with *SOC*, *TN*, and pH) was identified as one of the main factors affecting most herbaceous plants in mobile dunes (Zuo et al. 2009b). In our study, *EC* at both layers was evidently different in the *LPC* and in the *AOC* ($P < 0.05$), which was similar to the variation of vegetation *IVs*. pH at both layers, however, did not change obviously from the *LPC* to the *AOC*. Correlation analyses also showed that species richness was positively correlated with *EC* at both layers ($P < 0.01$), while pH showed a negative correlation with species diversity only at 0–5-cm ($P < 0.05$). Hence, *EC* in this study showed a closer correlation with vegetation changes than pH along the ecotone. Sýkora et al. (2004), however, documented that acidification (associated with pH) was an underlying soil process driving vegetation succession. The inconsistency between the results of this study and that of Sýkora et al. (2004) may have been caused by differences between semiarid sandy land and coastal dunes.

The models of plant species richness and diversity produced by stepwise regression analyses showed that only soil total nitrogen, electrical conductivity at 0–5-cm, and available K at 5–10-cm were selected as the predictors. All other soil variables were excluded from the models. This result suggested that although vegetation characteristics had intimate relationships with soil variables such as *SOC1*, *SOC2*, *TN1*, *TN2*, *EC1*, and *EC2*, only *TN1*, *EC1*, and *AK2* can determine the value of plant attributes.

5 Conclusions

Soil properties at surface and subsurface layers have different *SV* models, indicating a change of horizontal heterogeneity at different depths. *SOC* and *EC* shared larger spatial heterogeneity at subsurface layers than that at surface layers, which is due to wind erosion in this area. Smaller scale sampling intervals on the horizontal level would be useful for determining the spatial heterogeneity of some properties such as pH at depth of 5–10-cm and species evenness. Spatial heterogeneity in soil layers at 5–10-cm can explain plant species diversity best. Soil nutrients decreased at both depths along the ecotone. Vegetation characteristics could be closely correlated to *SOC*, *TN*, and *EC*, whereas only *TN1*, *EC1*, and *AK2* are the main factors affecting the vegetation succession in this critical area of desertification.

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