Environ Geol (2009) 58:1227–1237
DOI 10.1007/s00254-008-1617-1

ORIGINAL ARTICLE

Vegetation pattern variation, soil degradation and their relationship along a grassland desertification gradient in Horqin Sandy Land, northern China

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Received: 15 February 2008 / Accepted: 16 October 2008 / Published online: 12 November 2008

Abstract The Horqin Sandy Land is one of the most severely desertified regions in northern China. Plant communities and soil conditions at five stages of grassland desertification (potential, light, moderate, severe and very severe) were selected for the study of vegetation pattern variation relating to soil degradation. The results showed that vegetation cover, species richness and diversity, aboveground biomass (AGB), underground biomass, litter, soil organic carbon (C), total nitrogen (N), total phosphorus (P), electrical conductivity, very fine sand (0.1–0.05 mm) content and silt (0.05–0.002 mm) content decreased with the desertification development. Plant community succession presented that the palatable herbaceous plants gave place to the shrub species with asexual reproduction and sand pioneer plants. The decline of vegetation cover and AGB was positively related to the loss of soil organic C and total N with progressive desertification ($P < 0.01$). The multivariate statistical analysis showed that plant community distribution, species diversity and ecological dominance had the close relationship with the gradient of soil nutrients in the processes of grassland desertification. These results suggest that grassland desertification results in the variation of vegetation pattern which presents the different composition and structure of plant community highly influenced by the soil properties.

Keywords CCA · Desertification · Horqin Sandy Land · Soil properties · Vegetation pattern

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Introduction

Desertification means land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities (UNEP 1994; Rubio and Bochet 1998). Vegetation and soil degradation are two important processes in land desertification (Dregne 1998; Li et al. 2006a, b). The influence of desertification on regional environmental change is one of the most important research focuses in desertification study. Charney et al. (1977) revealed that the drought and dynamics of desert in the Sahara are controlled by a biogeophysical feedback mechanism. Li et al. (2003) assessed the variation of sand transportation rate in sandy grasslands at different levels of desertification in northern China. Li et al. (2006a, b) reported that influence of desertification on vegetation pattern variations in the cold semi-arid grasslands of Qinghai-Tibet Plateau, Northwest China. However, ecologists have more focused on the following ecological research in recent years: (1) changes in ecosystem structure and function (e.g., species diversity and production) are examined in desertification processes (Verstraete and Schwartz 1991; Cheng et al. 2007) and (2) the degradation in desertified area usually accompanies a decrease in soil quality together with a regression of ecological succession (Rodríguez Rodríguez et al. 2005). In addition, it has been reported that an increase in the heterogeneity of soil nutrient and vegetation may be linked with desertification processes (Schlesinger et al. 1990, 1996). The research focusing on the spatial distribution of plants, soil nutrients and ecosystem functions is important to understand the processes of grassland desertification (Cheng et al. 2007).

Horqin Sandy Land (commonly called "Horqin sandy grassland") lies in the semi-arid area of southeast Inner Mongolia. Primary landscape in Horqin Sandy Land is the scattered tree grassland. This region has suffered severe desertification over recent decades, due to the long-term influence of extensive fuelwood gathering, heavy grazing and reclamation (Zhu and Wang 1992; Li et al. 2003, 2005). Wang (2000) evaluated landscape changes from the 1960 s to the 1990 s in the Horqin region by interpreting satellite images, historical maps, meteorological and socioeconomic data. The mean annual rate of desertification has risen from 1,142 km^2 in the 1960 s to 2,460 km^2 in the 1990 s (Wang 2000; Li et al. 2005). To date, most sandy grasslands have evolved into mobile, semi-mobile, semi-fixed and fixed sandy lands corresponding to very severe, severe, moderate and light desertification (Zhu and Chen 1994; Li et al. 2003, 2005, 2006a, b). In recent years, desertification and its impact on the Horqin region have been intensively studied (Li et al. 2002, 2003, 2005; Zhao et al. 2005; Zhang et al. 2005; Su et al. 2006; Liu et al. 2006; Zuo et al. 2007). However, the variation in vegetation pattern and the concomitant changes in soil properties have not been clarified in the processes of grassland desertification.

The vegetation is a good indicator of an ecosystem's overall function in arid and semi-arid areas. Alterations in the vegetation pattern over time can result in changes on the distributions of both living organism and soil resource. Soil organic carbon, nitrogen and phosphorus are very important to maintain ecosystem function because of their direct roles in many ecosystem processes, e.g., plant growth and carbon cycle (Robertson et al. 1988). Many studies have suggested that plant distributions in arid regions are strongly affected by soil resource variations (Puignaire et al. 1996; Daiyuan et al. 1998; Maestre and Cortina 2002). Some hypotheses for desertification in semi-arid grasslands indicate that grassland desertification is often characterized by vegetation replacement, e.g., perennial herbaceous species are often replaced by long-lived woody shrubs (Schlesinger et al. 1990, 1996; Schlesinger and Pilmanis 1998). Desertification results in the change of vegetation pattern and structure e.g., change from grassland to shrubland due to increasing spatial and temporal variation of water, nutrient and other soil properties (Dunkerley 2000; Sperry and Hacke 2002). Thus, it is necessary to understand the relationship between vegetation and soil along a grassland desertification gradient in Horqin Sandy Land.

The overall aim of this paper was to describe how sandy vegetation and soil respond to grassland desertification in Horqin Sandy Land. The specific objectives of this study were: (1) to examine patterns and dynamics of plant species composition and diversity along a desertification gradient of sandy grassland; (2) to detect the relationship between vegetation pattern and soil properties in the processes of grassland desertification.

Materials and methods

Study area

This study was conducted in the south-western (42°55′ N, 120°42′ E; elevation approximately 360 m) Horqin Sandy Land, Inner Mongolia, China. This area is a temperate zone with the continental monsoon climate, receiving average annual precipitation of 360 mm, with 75% of this in the growing season of June to September. The annual mean open-pan evaporation is about 1,935 mm. The annual mean temperature is around 6.4°C with the minimum monthly mean temperatures of −13.1°C in January and the maximum 23.7°C in July. The annual mean wind velocity is in the range of 3.2–4.1 m s^{-1} (Zhu and Chen 1994).

The distribution of vegetation patches and soil properties at relatively small scale within a degraded sandy grassland show high degree of spatial heterogeneity (Su et al. 2006). The zonal soils are identified as degraded sandy chestnut soils, which are mostly equivalent to the Orthi-Sandic Entisols of sand origin in terms of the FAO-UNESCO system. These soils characterized by their coarse texture and loose structure with high proportion of sand (85–95%) and low organic matter content (0.15–0.5% soil organic C), are highly susceptible to wind erosion. A rapidly growing human population within the last 50–100 years has produced increasing impacts from grazing and cultivation and has affected the grassland desertification.

Desertification grades

There are many quantitative and/or qualitative criteria for assessing the degree of grassland desertification (Mabbutt 1986; Dregne 1991; Zhu and Wang 1992; Zhu and Chen 1994; Li et al. 2003, 2005, 2006a, b). When wind erosion and sand accumulation in the grassland are obvious, the desertification process started. If vegetation cover is reduced to 50–70% and area of shifting sand accounts for about 1–2% of the total grassland area, grassland is regarded as lightly desertified (LD) area, e.g., fixed sandy land. If vegetation cover is reduced to 30–50% and area of shifting sand accounts for about 5–20% of the total grassland area, then grassland is regarded as moderately desertified (MD) area, e.g., semi-fixed sandy land. If vegetation cover is reduced to 10–30% and area of shifting sand accounts for about 20–50% of the total grassland area, then grassland is regarded as severely desertified (SD) area, e.g., semi-mobile sandy land. If vegetation cover is reduced to <10% and area of shifting sand accounts for >50% area of the total grassland, then grassland is regarded as very SD (VSD) area, e.g., mobile sandy land. Also, researchers working in this area think that if vegetation cover is >70%, grassland may be regarded as the potentially desertified (PD) area. According to the level grades of grassland desertification, this study was conducted in different 15 plant communities chosen along a gradient from potential to very severe desertification.

Vegetation survey

All data were collected in mid-August 2005. The chosen 15 plant communities at five desertification stages had the similar topographic conditions (open and flat field site). In each plant community, 50×50 m^2 plot was established for this study. Quadrats in vegetation survey were 5×5 m^2 for shrubs and 1×1 m^2 for herbs. Ten random quadrats shrubs and herbs were placed in each plant community plot to measure plant height (maximum), species abundance and cover, respectively. A total of 300 quadrats were assigned to investigate plant community characteristics at five stages of grassland desertification. In each quadrat of herb survey, the litter was carefully collected, the aboveground biomass (AGB) of plant estimated by harvest method and six replicated soil cores of the underground biomass (UGB) were taken in 20 cm depth with a soil auger (8 cm in diameter). This range was chosen because most of the roots of herbs and semi-shrubs lie in this depth in this area. In the laboratory, UGB collected in each soil core was first carefully washed. The litter, AGB and UGB were dried at 60°C in hot air oven for 48 h and weighed.

Soil sampling

Concurrently, three mixed soil samples for laboratory analysis were randomly taken in each plot of 15 plant communities. Each soil sample was a mixture of 15 random soil cores (0–20 cm depth) using 3-cm-diameter soil auger in order to reduce soil heterogeneity in each community. With the same auger, 45 additional replicate cores were taken in each plot to measure soil water (SW) content at depth of 0–20 cm. In addition, 45 soil bulk densities (BD) in each plot were measured by the core method. Soil samples were pretreated through a 2-mm screen to remove roots and other debris. Soil particle size was measured by the pipette method in a sedimentation cylinder, using sodium hexamethaphosphate as the dispersing agent (ISSCAS 1978). Soil pH and electrical conductivity (EC) were measured in a 1:1 soil–water slurry and in a 1:5 soil–water aqueous extract (Multiline F/SET-3, Germany), respectively. Soil organic carbon (C) was measured by the dichromate oxidation method of Walkley and Black (Nelson and Sommers 1982), total nitrogen (N) by the Kjeldahl procedure (ISSCAS 1978) and total phosphorus (P) by UV-1601 spectrophotometer (Japan), after $H_2SO4–HClO_4$ digestion (ISSCAS 1978). Soil available nitrogen (AN) was measured by the alkaline diffusion method and available phosphorus (AP) was measured by the Bray method (ISSCAS 1978). Potassium (K) and available potassium (AK) were measured by flame spectrophotometry (ISSCAS 1978).

Data analysis

The relative important value (IV) of species in each plot was calculated from the mean of relative cover, relative height and relative abundance (Zhang et al. 2005). Species diversity was calculated by the Shannon–Wiener index (*H*). Species ecological dominance was calculated by the Simpson index (*D*). In order to study the relationship between the vegetation pattern and soil properties, a canonical correspondence analysis (CCA) (Ter Braak 1986) was used. Data matrices of the soil variables (mean value in each plot) and plant IV based on 15 plant communities were made (He et al. 2007; Zuo et al. 2008). Significance of species–soil correlation was tested by the distribution-free Monte Carlo test (1,000 permutations). In the Monte Carlo test, the distribution of the test statistics under the null hypothesis is generated by random permutations of cases in the environmental data (Jafari et al. 2004).

Differences of vegetation characteristics and soil properties among the different desertification stages were analyzed by the one-way analysis variance. Results were checked by Tukey's test. The statistical analyses were calculated by SPSS (version 13.0). The analysis of relationships between the distribution of plant communities and soil properties was performed using CANOCO v.4 software (Ter Braak and Smilauer 1998).

Results

Vegetation pattern variation in the processes of grassland desertification

Differences in species number between the five stages of desertification development were obvious (Table 1, $P < 0.01$), except between PD and LD ($P > 0.01$). There

Table 1 Changes on vegetation characteristics at the different grassland desertification stages

	PD	LD	MD	SD	VSD
Species number	34 ± 1.65[a]	32 ± 2.45[a]	20 ± 3.68[b]	12 ± 2.64[c]	6 ± 2.57[d]
Cover (%)	76.80 ± 3.60[a]	64.60 ± 4.66[b]	51.13 ± 0.58[c]	28.14 ± 7.64[d]	9.55 ± 0.57[e]
AGB (g m^{-2})	294.21 ± 20.65[a]	207.24 ± 19.20[a]	152.84 ± 20.04[b]	60.38 ± 8.05[c]	16.21 ± 7.21[d]
UGB (g m^{-2})	748.32 ± 394.21[a]	557.32 ± 236.93[a]	355.63 ± 159.56[b]	180.45 ± 3.04[c]	78.14 ± 15.25[d]
Litter (g m^{-2})	208.42 ± 131.15[a]	142.4 ± 32.11[a]	66.03 ± 5.55[b]	47.73 ± 1.14[c]	3.75 ± 0.75[d]
H	2.27 ± 0.15[a]	2.45 ± 0.15[a]	1.98 ± 0.45[b]	1.80 ± 0.04[b]	1.24 ± 0.24[c]
D	0.14 ± 0.03[a]	0.12 ± 0.02[a]	0.21 ± 0.01[b]	0.25 ± 0.01[b]	0.39 ± 0.10[c]

Values represent mean ± SE

PD potential desertification, *LD* light desertification, *MD* moderate desertification, *SD* severe desertification, *VSD* very severe desertification, *AGB* aboveground biomass, *UGB* underground biomass, *H* Shannon–Wiener index, *D* Simpson index

The different letters from mean values indicate statistical difference among different desertification stages ($P < 0.01$)

was no significant difference in the species diversity index (*H*) and ecological dominance index (*D*) between PD and LD, nor between MD and SD ($P > 0.01$), but there were a decreasing trend in species diversity index and an increasing trend in ecological dominance index in the processes of grassland desertification. The values of vegetation cover, AGB, UGB and litter also showed a decreasing trend form PD to VSD, and the significant differences were obvious between the different grassland desertification stages ($P < 0.01$) except AGB, UGB and litter between PD and LD ($P > 0.01$).

The relative IV for dominant species in plant communities at the different desertification stages are shown in Table 2. The dominance of palatable herbaceous plants and semi-shrubs in grassland decreased with the development of grassland desertification, e.g., *Cleistogenes squarrosa*, *Lespedeza davurica*, *Eragrostis pilosa* and *Artemisia frigida*. Whereas, dominance of some psammophytes and indicator species adapted to the semi-mobile dunes and mobile dunes, *Artemisia halodendron*, *Ixeris denticulata*, *Agriophyllum squarrosum*, *Inula salsoloides* and *Sonchus oleraceus*, increased in the processes of grassland desertification. At the same time, a decrease in species numbers of perennial grasses, and an increase in dominance of shrub with asexual reproduction occurred from PD to SD. At the end of the degradation sequence (VSD) there were the pioneer sand plants.

Changes on soil physicochemical properties in the processes of grassland desertification

Soil water content, BD and particle size distributions at the different stages of grassland desertification are shown in Table 3. The SW content that is a dynamic variable influenced by plant and precipitation, had no clear differences ($P > 0.01$) between the different grassland desertification stages. Soil BD increased from 1.51 ± 0.45 g cm^{-3} in PD to 1.64 ± 0.01 g cm^{-3} in VSD, and the significant differences were obvious ($P < 0.01$) except between LD and MD, and between SD and VSD ($P > 0.01$). Generally, soil texture becomes coarser with the development of grassland desertification. In this study, very fine sand content and silt content declined from 28.00 ± 9.98 and 24.33 ± 6.74% in PD to 0.96 ± 0.42 and 1.43 ± 0.49% in VSD, respectively, and there were differences in very fine sand content ($F = 15.02$, $P < 0.05$) and silt content ($F = 6.82$, $P < 0.05$) among the different desertification stages.

Soil chemical characteristics greatly varied in the grassland desertification processes (Table 4). EC, soil organic C, total N and total P showed an apparent decreasing trend, e.g., they declined from 69.33 ± 28.04 dS m^{-1}, 6.32 ± 0.81, 0.45 ± 0.05 and 0.39 ± 0.12 g kg^{-1} in PD to 19.67 ± 2.890 dS m^{-1}, 49 ± 0.11, 0.13 ± 0.01 and 0.08 ± 0.01 g kg^{-1} in VSD respectively. Therefore, the very SD grassland stored the less soil organic C, total N and total P. Also, AN and AK decreased floatingly in the desertification processes, and they were significant differences in AN ($P < 0.01$) and AK ($P < 0.01$) among the different desertification stages. The change of soil potassium was relatively unclear in the processes of desertification, and no significant differences ($F = 0.33$, $P > 0.05$) were found among the different desertification stages.

Relationship between vegetation pattern and soil properties

Correlation analysis of plant community characteristics and soil physicochemical properties are shown in Table 5. Correlation analysis indicated that there was a significant positive correlation ($P < 0.01$) between soil organic C, total N, cover and AGB. In addition, there were a significant positive correlation ($P < 0.01$) between total N, total

Table 2 Changes on important values (IV, mean) for dominant species in plant communities at the different grassland desertification stages

Species	Life-form	Potential desertification			Light desertification					Moderately desertification		Severe desertification		Very severely desertification		
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Artemisia halodendron	S							1.81		17.10	14.35	22.58	20.52		0.86	
Lespedeza davurica	SS, PL	13.65	16.45	15.57	2.30	1.22	7.39	0.99		0.84	0.31					
Artemisia frigida	SS				19.31	16.03	23.48	11.22	12.05							
Ixeris denticulata	AF									1.98	2.17	34.42	17.52			
Corispermum elongatum	AF	2.63				2.42	1.24	3.75		4.35	4.33	11.13	7.80	7.69		3.72
Setaria viridis	AG		10.84	16.99	9.39	12.86	18.26	9.33	6.27	9.75	9.79	7.36	9.45	2.85	24.98	12.51
Agriophyllum squarrosum	AF												1.52	60.02	14.66	13.31
Chenopodium aristatum	AF									1.79			1.70	16.40	6.71	11.71
Sonchus oleraceus L.	AF														11.25	50.01
Inula salsoloides	AF													9.30	38.02	7.13
Aristida adscensionis	AG		5.98	3.96	3.16	11.53	4.13	8.50	5.61	2.14	4.18	1.58				
Eragrostis pilosa	AG			2.32	22.40	4.46	3.68	6.16	15.39							
Euphorbia humifusa	AF	0.48	0.41		2.73	13.98	1.10	2.90	1.48	20.97	9.49	7.59	0.76			
Bassia dasyphylla	AF			1.45	3.17	2.93	1.95	4.02	30.86	5.24	1.23	0.44	1.82			
Digitaria ciliaris	AG				5.26	3.80	7.39	15.10	3.58	11.06	20.02	1.71				
Chloris virgata	AG		0.89	7.86	11.07	0.79	1.76	0.29	1.96							
Tribulus terretris	AF	0.58			0.77	2.09	7.59		0.24							
Cleistogenes squarrosa	PG	32.59	7.61	8.46	2.07		2.42	2.01	3.56		2.15					
Tragus mongolorum	AG	26.37							0.68							
Phragmites communis	PG		21.71				1.13		1.62				23.97			
Artemisia scoparia	AF	13.48	29.51	28.80	10.48	12.85	4.82	6.34	6.68							
Melissitus ruthenicus	PL					6.52	5.13	12.86	4.48	21.27	18.45	10.28				

Community abbreviations are shown in the appendix

AF annual forbs, *AG* annual grass, *PF* perennial forbs, *PG* perennial grass, *PL* perennial legume, *S* shrub, *SS* semi-shrub

Table 3 Soil physical properties at the different grassland desertification stages

	PD	LD	MD	SD	VSD	*F*-value	*P*-value
SW (%)	4.78 ± 1.10^{a}	3.25 ± 0.33^{a}	3.00 ± 0.10^{a}	3.23 ± 0.10^{a}	3.67 ± 0.18^{a}	4.37	0.03
BD (g cm^{-3})	1.51 ± 0.45^{a}	1.58 ± 0.01^{b}	1.60 ± 0.02^{b}	1.62 ± 0.02^{c}	1.64 ± 0.01^{c}	12.24	0.00
Particle size (%)							
Coarse sand (0.5–0.25 mm)	16.31 ± 8.95^{a}	29.99 ± 7.15^{a}	36.78 ± 0.62^{a}	33.22 ± 1.15^{a}	33.35 ± 5.81^{a}	3.41	0.05
Fine sand (0.25–0.10 mm)	28.06 ± 11.51^{a}	54.06 ± 6.11^{b}	48.73 ± 0.86^{b}	60.17 ± 0.95^{b}	61.66 ± 4.76^{b}	7.51	0.00
Very fine sand (0.1–0.05 mm)	28.00 ± 9.98^{a}	7.7 ± 2.67^{b}	6.89 ± 0.15^{b}	3.09 ± 0.10^{c}	0.98 ± 0.41^{d}	15.02	0.00
Silt (0.05–0.002 mm)	24.33 ± 6.74^{a}	5.33 ± 1.13^{b}	5.03 ± 0.08^{b}	2.77 ± 0.44^{c}	1.41 ± 0.51^{d}	6.82	0.01
Clay (<0.002 mm)	2.37 ± 0.34^{a}	2.58 ± 0.42^{a}	2.68 ± 0.15^{a}	2.29 ± 0.07^{a}	1.98 ± 0.04^{a}	0.97	0.47

Values represent mean ± SE

PD potential desertification, *LD* light desertification, *MD* moderate desertification, *SD* severe desertification, *VSD* very severe desertification

The different letters from mean values indicate statistical difference among different desertification stages ($P < 0.01$)

P, AN, silt and soil organic C, and a significant negative correlation ($P < 0.01$) between soil BD, sand (>0.05 mm), and soil organic C. Moreover, regression analyses of the relationship between soil organic C, total N and particle size proportions showed that soil organic C and total N tended to be associated with fines (<0.1 or <0.05 mm)

Table 4 Soil chemical properties at the different grassland desertification stages

	PD	LD	MD	SD	VSD	*F*-value	*P*-value
PH	8.28 ± 0.16[a]	8.04 ± 0.13[a]	7.91 ± 0.04[a]	8.28 ± 0.01[a]	7.96 0.17[a]	3.75	0.04
EC (dS m^{-1})	69.33 ± 28.04[a]	31.80 ± 2.59[b]	29.33 ± 0.58[b]	28.00 ± 0.02[b]	19.67 ± 2.89[b]	6.79	0.01
C (g kg^{-1})	6.32 ± 0.81[a]	3.36 ± 0.31[b]	1.64 ± 0.25[c]	1.02 ± 0.02[d]	0.49 ± 0.11[e]	77.55	0.00
N (g kg^{-1})	0.45 ± 0.05[a]	0.31 ± 0.02[b]	0.21 ± 0.03[c]	0.15 ± 0.02 [cd]	0.13 ± 0.01[de]	81.65	0.00
P (g kg^{-1})	0.39 ± 0.12[a]	0.19 ± 0.02[b]	0.14 ± 0.01[bc]	0.12 ± 0.02[bc]	0.08 ± 0.01[c]	15.31	0.00
K (g kg^{-1})	29.17 ± 4.76[a]	25.00 ± 8.47[a]	28.33 ± 1.44[a]	29.16 ± 1.44[a]	27.50 ± 0.00[a]	0.33	0.85
AN (g kg^{-1})	20.63 ± 4.54[a]	15.10 ± 1.13[b]	9.14 ± 0.83[c]	6.23 ± 0.21[c]	7.70 ± 0.96[c]	19.42	0.00
AP (g kg^{-1})	7.00 ± 2.20[a]	13.84 ± 3.27[b]	8.45 ± 2.08[a]	8.69 ± 0.55[ab]	8.21 ± 0.61[a]	6.15	0.01
AK (g kg^{-1})	86.67 ± 5.77[a]	110 ± 14.14[b]	86.67 ± 0.02[a]	70 ± 0.01[a]	50 ± 0.01[c]	15.01	0.00

Values represent mean ± SE

PD potential desertification, *LD* light desertification, *MD* moderate desertification, *SD* severe desertification, *VSD* very severe desertification, *EC* electrical conductivity, *C* soil organic carbon, *N* total nitrogen, *P* total phosphorus, *AN* available soil nitrogen, *AP* available phosphorus, *K* potassium, *AK* available potassium

The different letters from mean values indicate statistical difference among different desertification stages ($P < 0.01$)

rather than with sands (>0.1 or >0.05 mm) in the grassland desertification processes (Table 6).

The diagram originated by first two axes of the CCA (Fig. 1, Table 7) showed that the important soil variables affecting plant community distribution were included in the survey. In CCA ordination diagram, plant community types are represented by circles and codes, and soil variables are represented by vectors. A Monte Carlo permutation test indicated that all the canonical axes were significant ($P < 0.005$). The first axis highly correlated with the soil organic C ($r = -0.73$, $P < 0.01$), total N ($r = -0.75$, $P < 0.01$), AN ($r = -0.65$, $P < 0.01$) and AK ($r = -0.80$, $P < 0.01$), which showed the gradient of soil nutrients in the processes of grassland desertification. The second axis was highly correlated with SW content ($r = 0.70$, $P < 0.01$), sand content ($r = -0.66$, $P < 0.01$) and silt content ($r = 0.64$, $P < 0.01$). The two axes explained 25.40 and 16.00% of cumulative percentage variance, respectively. The first axis represented the key factors in soil properties affecting plant community distribution.

Relationship between characteristic of community structure and soil properties

The species diversity and ecological dominance are two important ecological indexes for describing the structure and function of plant community (Liu and Zhou 1996). In order to study the relationship between the characteristics of plant community structure and soil properties in the processes of grassland desertification, Shannon–Wiener diversity index (*H*) and Simpson dominance index (*D*) were used in this paper. The correlation analysis indicated that the *H* and *D* were not correlated to soil properties ($P > 0.01$) except AK (Table 5). However, the results of regression analysis from Table 8 showed that the first axis component (Y_1) had significant linear relationships with *H* and *D*, respectively. Moreover, Y_1 had a multivariate linear relationship with *H* and *D*. These results also showed that the changes on species diversity and ecological dominance had a close relationship with the gradient of soil nutrients in the processes of grassland desertification.

Discussion

Horqin Sandy Land, with its wind-sandy environment and poor sandy soils, has undergone the severe land desertification in the past decades due to excessive removal of natural vegetation for fuel, overgrazing and extensive cultivation of the natural grasslands (Zhao et al. 2005). Consequently, the physical structure and chemical component of soil are changed in the desertification processes, reducing soil nutrients, making land barren and decreasing land productivity (Li et al. 2006a, b). Our results showed that the vegetation cover, species number and diversity indices, biomass, litter, soil nutrient, fine sand content and very fine sand content decreased in the processes of grassland desertification. The result is consistent with the previous studies, supporting the conclusion that desertification process greatly changed the vegetation pattern and soil properties of sandy grassland (Li et al. 2006a, b; Zuo et al. 2007). In particular, desertification process resulting in the changes on soil nutrient levels in sandy grasslands, promotes the composition and structure of grassland ecosystem to evolve the different spatial allocations of production (Cheng et al. 2007). Our studies indicate that plant communities in potential and light desertification

Table 5 Pearson correlation among plant community characteristics, soil physical and chemistry properties

	Cover	AGB	*D*	*H*	pH	EC	BD	SW	C	N	P	K	AN	AP	AK	Sand	Silt	Clay
Cover	1.00																	
AGB	0.86**	1.00																
D	−0.71**	−0.73*	1.00															
H	0.76**	0.73**	0.96**	1.00														
pH	0.32	0.27	0.16	0.03	1.00													
EC	0.60*	0.48	0.22	0.15	0.69**	1.00												
BD	−0.60*	−0.59*	−0.41	−0.35	−0.53**	−0.89**	1.00											
SW	0.18	0.15	−0.15	−0.26	0.73**	0.85**	−0.68**	1.00										
C	0.85**	0.71**	0.41	0.41	0.59*	0.86**	−0.85**	0.62*	1.00									
N	0.89**	0.76**	0.44	0.45	0.56*	0.81**	−0.80**	0.57*	0.99**	1.00								
P	0.74**	0.57*	0.30	0.27	0.63*	0.96**	−0.91**	0.77**	0.95**	0.92**	1.00							
K	−0.09	−0.06	−0.20	−0.28	0.38	0.19	−0.09	0.33	0.08	0.05	0.10	1.00						
AN	0.81**	0.66**	0.35	0.37	0.52*	0.83**	−0.75**	0.62**	0.95**	0.96**	0.92**	0.04	1.00					
AP	0.26	0.12	0.43	0.56*	−0.36	−0.27	0.21	−0.47	0.05	0.06	−0.11	−0.55*	0.14	1.00				
AK	0.79**	0.76**	0.76**	0.86**	0.04	0.12	−0.24	−0.27	0.49	0.54	0.27	−0.34	0.46	0.59*	1.00			
Sand	−0.59*	−0.47	−0.16	−0.09	−0.65*	−0.99**	0.88**	−0.87**	−0.86**	−0.82**	−0.96**	−0.24	−0.85**	0.29	−0.07	1.00		
Silt	0.57*	0.45	0.16	0.08	0.66**	0.99**	−0.89**	0.87**	0.85**	0.80**	0.96**	0.23	0.83**	−0.31	0.06	−0.99**	1.00	
Clay	−0.25	−0.10	−0.16	−0.11	−0.31	−0.22	0.25	0.01	−0.31	−0.21	−0.22	−0.19	−0.19	−0.01	−0.23	0.19	−0.23	1.00

AGB aboveground biomass, *D* Simpson index, *H* Shannon–Wiener (*H*) index, *EC* electrical conductivity, *SW* soil water content, *BD* soil bulk density, *C* soil organic carbon, *N* total nitrogen, *P* total phosphorus, *AN* available soil nitrogen, *AP* available phosphorus, *K* potassium, *AK* available potassium, *Sand* sand content of >0.05%

* Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)

Table 6 Relationship between soil organic C, total N and particle proportion

	Particle size (mm)	Linearity regression equation	*P*-value	R^2	*N*
C	>0.1	$C = -0.0913X_1 + 10.1620$	0.000	0.8060	15
	<0.1	$C = 0.0925X_2 + 1.0216$	0.000	0.7996	15
	<0.05	$C = 0.1821X_3 + 0.9636$	0.000	0.7250	15
N	>0.1	$N = -0.51X_1 + 0.6687$	0.000	0.7308	15
	<0.1	$N = 0.51X_2 + 0.1611$	0.000	0.7188	15
	<0.05	$N = 0.0100X_3 + 0.1587$	0.000	0.644	15

C soil organic carbon, *N* total nitrogen

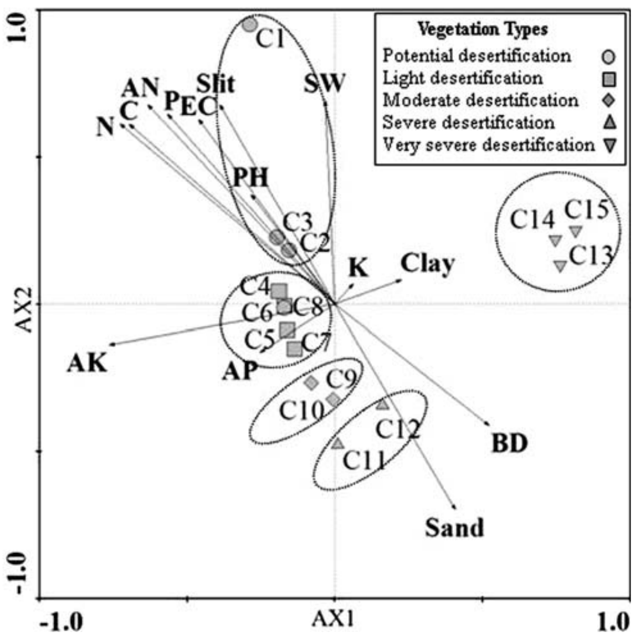

Fig. 1 Canonical correspondence analysis two-dimensional ordination diagram of 15 communities based on plant important values and soil variables (*EC* electrical conductivity, *SW* soil water content, *BD* soil bulk density, *C* soil organic carbon, *N* total nitrogen, *P* total phosphorus, *AN* available soil nitrogen, *AP* available phosphorus, *K* potassium, *AK* available potassium, *Sand* sand content of >0.05%. Community abbreviations are shown in the appendix)

stages support the higher productivity than that of shrub-dominated communities in moderate and severe desertification stages.

Degradation of an ecosystem usually results in a decrease in soil quality together with a regression of the ecological succession (Rodríguez Rodríguez et al. 2005). According to the state-and-transition model as described by Westoby (1989) and Milton and Hoffman (1994), we provided simple state-and-transition models giving the vegetation characteristics to describe the situation of sandy grasslands degradation in semi-arid area (Fig. 2). Our results indicate that the palatable grass and leguminous plant have given place to the shrub vegetation with asexual reproduction and pioneer sand plants that are tolerant to sand burial and barren soils in the processes of grassland desertification. With progressive desertification, the ecological replacement of unpalatable semi-shrub and shrub was obvious, such as *Artemisia frigida* semi-shrub and *Artemisia halodendron* shrub. The unpalatable plant of *Artemisia frigida* replaced gradually *Cleistogenes*

Table 7 Cumulative percentage variance, eigenvalue and species–soil correlation coefficients for the first two axes of CCA

	Axis	
	AX1	AX2
pH	−0.34	0.34
EC	−0.52*	0.58*
BD	0.59*	−0.38
SW	−0.03	0.70**
C	−0.73**	0.55*
N	−0.75**	0.55*
P	−0.61**	0.59*
K	0.05	0.06
AN	−0.65**	0.60*
AP	−0.24	−0.19
AK	−0.80**	−0.17
Sand	0.45	−0.66**
Silt	−0.44	0.64**
Clay	0.28	0.14
Eigenvalue	0.68	0.43
Species–soil correlations	1.00	1.00
Cumulative percentage variance (%)	25.40	41.40

EC electrical conductivity, *SW* soil water content, *BD* soil bulk density, *C* soil organic carbon, *N* total nitrogen, *P* total phosphorus, *AN* available soil nitrogen, *AP* available phosphorus, *K* potassium, *AK* available potassium, *Sand* sand content of >0.05%

* Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)

Table 8 Regression analysis between CCA axis values and plant community structure

Axis	Community structure	Coefficient		Regression coefficient, R^2	*P*
		B_0	B_1		
Y_1	*H*	−1.49	8.21	0.63	0.000
Y_1	*D*	4.34	−2.06	0.68	0.000
Y_2	*H*	−0.46	2.58	0.08	0.320
Y_2	*D*	1.55	−0.73	0.11	0.230

$Y_1 = 4.29 + 0.07\ H - 2.04\ D$, $R^2 = 0.68$, $P < 0.005$; $Y_2 = 4.50 - 4.41\ H - 1.75\ D$, $R^2 = 0.13$, $P < 0.5$

H Shannon–Wiener index, *D* Simpson index, Y_1 the first axis component, Y_2 the second axis component

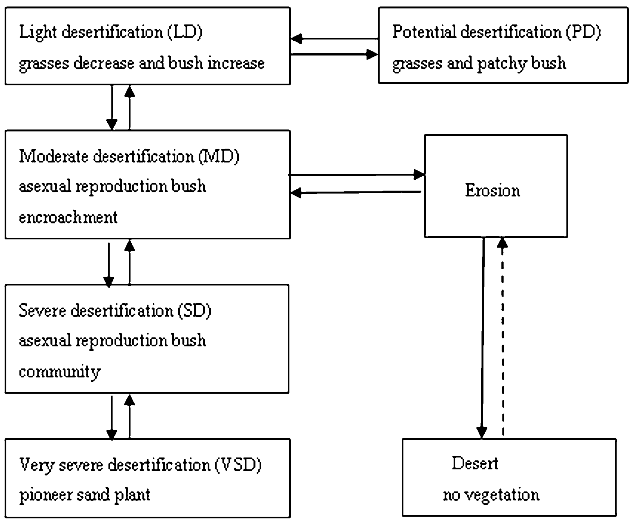

Fig. 2 Simple state-and-transition models for vegetation degradation in semi-arid sandy grasslands

squarrosa and *L. davurica* with the development of grassland desertification and eventually became the dominant plant in LD. At the same time, due to strong wind erosion, sand burial phenomena emerge in desertification processes. Sand burial is an environmental stress factor commonly encountered in arid and semi-arid desertified grasslands (Maun and Lapierre 1986; Brown 1997). As desertification continued, some burial-tolerant plants, such as *Artemisia halodendron* with asexual reproduction could survive this environment to increase its dominance and became the dominant in SD. These results, in a certain degree, support the hypothesis that grassland desertification is often characterized by vegetation replacement, e.g., perennial herbaceous species are often replaced by long-lived woody shrubs (Schlesinger et al. 1990, 1996; Schlesinger and Pilmanis 1998). At very severely desertification stage, *Agriophyllum squarrosum* of pioneer sand plant was adapted to barren soils and grew vigorously in VSD (Nemoto and Lu 1992; Zhang et al. 2005).

Climate, topography and soil exert important influences on the plant distribution (Huerta-Martínez et al. 2004; Jafari et al. 2004). However, soil is very important for plant growth and is a function of climate, organisms, topography, parent material and time (Jafari et al. 2004). Commonly, the sandy grasslands in this area are characterized by a great number of over stocking management (overgrazing) (Zhao et al. 2005). The main driving force of grassland desertification in Horqin Sandy Land is wind erosion. The decline of vegetation cover caused by overgrazing disturbance accelerates directly sand ground erosion by wind (Zhao et al. 2005). Wind erosion results in the enlargement of bare patches on dunes, and at the same time it sorts the soil materials by removing fine size fractions and leaving a more coarse-textured soil behind (Su et al. 2004). Moreover, the rapid soil erosion can cause the topographic changes which can be partly attributed to the soil redistribution resulting from erosion of bare soil openings and from the trapping of windblown soil by grasses (depositional process) as plant growth occurs (Martinez-Turanzas et al. 1997). Topography may influence the accumulation and export of nutrients and soil particles (Sebastiá 2004), as well as the redistribution of soil resources on sand dune (Zuo et al. 2008). Our study indicate that desertification process results in the vegetation degradation and the changes of physical structure and chemical component of soils in sandy grasslands, consequently, the changes of soil nutrients further influence the plant distribution.

The conceptual model presented by Sala et al. (1997) hypothesizes that the dominance of shrubs or grasses is related to soil texture. Our results showed that the removal of fine particle fractions directly resulted in the decrease in soil organic C and total N in the processes of desertification, supporting the previous study that wind erosion can cause a loss of soil fine particles and increase soil coarseness in sandy grassland (Su et al. 2004). However, we do not fully support the hypothesis because plant distribution is also determined by the effects of disturbance (e.g., wind erosion) and resource heterogeneity (e.g., soil nutrient) on the competitive advantages of both bush and grasses (Li et al. 2006a, b). In addition, desertification processes can not only promote changes in soil texture, but also lead to the burial phenomena. Owing to the decline of vegetation cover and litter accumulation disturbed by overgrazing, the long-term wind erosion results in soil coarsening and loss of soil nutrients and increases the spatial and temporal variation of soil properties. Consequently, there had the different levels of soil nutrients at different grassland desertification stages in Horqin Sandy Land.

Although there is much literature that has studied the distribution of vegetation patches in desert and arid zones in relation to soil properties that condition an unequal distribution of the soil moisture regime (Schreiber et al. 1995; Puigdefábregas et al. 1999; Domingo et al. 2001; Rodríguez Rodríguez et al. 2005), we consider that our situation is not comparable. There were no significant differences in SW contents at different stages of grassland desertification (Table 3). Therefore, they are not expected to have different soil moisture regimes and vegetation growth after the rains. However, soil nutrient has directly affected plant growth and is one of the most important factors affecting the pattern of grassland plant communities (Maestre et al. 2003). Moreover, the shrublands are vulnerable to losses of soil nutrients resulting in a progressive degradation of productive capacity of the ecosystem over a long period (Schlesinger et al. 1990; Huenneke et al. 2001). The variation in species diversity can be linked to the ecological gradients of environment (Palmer 1992). Thus, the decline of biomass or species diversity is also related to the loss of soil nutrients from the ecosystem with progressive desertification.

Conclusions

It has been established that the degradation of the sandy grassland resulted from desertification shows a regression of the ecological succession accompanied by the processes of soil degradation causing a decrease in soil quality. Grassland desertification in Horqin Sand Land promotes changes in the vegetation pattern, e.g., shrub species and sand pioneer plants replace herbaceous plants in vegetation composition. Meanwhile, the occurrence of grassland desertification also results in soil property changes, e.g., coarsened soil texture and exhausted soil nutrients. Changes in soil properties are strongly related to vegetation pattern, including vegetation cover, diversity and biomass. In particular, grassland desertification process results in the changes on soil nutrient levels which further promote the composition and structure of plant community in degraded sandy grassland environments. In our restoration and management practices, much effort should be made to preserve sandy grassland with protected measures, to avoid the soil degradation and to enhance the natural restoration succession.

Acknowledgments Authors thank all the members of Naiman Desertification Research Station, Chinese Academy of Sciences (CAS), for their help in field work. Especially, we thank professors Tonghui Zhang, Yulin Li, Xinrong Li and Yongzhong Su for their kind assistance in our research work. We also wish to thank anonymous reviews for valuable comments on the manuscript. This paper was financially supported by the National Nature Science Foundation of China (40601008), the "Xibuzhiguang" Project of Chinese Academy of Sciences, the National Basic Research Program of China (973 Program) (2009CB421303), the Knowledge Innovation Programs of the Chinese Academy of Sciences (KZCX2-YW-431), National Key Technologies Support Program of China (2006BAC01A12, 2006BAD26B02).

Appendix: Community abbreviations at the different grassland desertification stages

C1, *Cleistogenes squarrosa* + *Tragus mongolorum* community; C2, *Artemisia scoparia* + *Phragmites communis* + *L. davurica* community; C3, *Artemisia scoparia* + *Setaria viridis* + *L. davurica* community; C4, *Eragrostis pilosa* + *Artemisia frigida* community; C5, *Artemisia frigida* + *Euphorbia humifusa* community; C6, *Artemisia frigida* + *Setaria viridis* community; C7, *Digitaria ciliaris* + *Melissitus ruthenicus* + *Artemisia frigida* community; C8, *Bassia dasyphylla* + *Eragrostis pilosa* + *Artemisiafrigida* community; C9, *M. ruthenicus* + *Euphorbia humifusa* + *Artemisia halodendron* community; C10, *D. ciliaris* + *M. ruthenicus* + *Artemisia halodendron* community; C11, *Ixeris denticulata* + *Artemisia halodendron* community; C12, *P. communis* + *Artemisia halodendron* + *Ixeris denticulata* community; C13, *Agriophyllum squarrosum* community; C14, *Inula salsoloides* + *Agriophyllum squarrosum* community; C15, *Sonchus oleraceus* + *Agriophyllum squarrosum* community

References

Brown JF (1997) Effect of experimental burial on survival, growth and resource allocation of three species of dunes plants. J Ecol 85:151–158

Charney JG, Quirk WJ, Chow SH, Kornfield J (1977) A comparative study of the effects of albedo change on drought in semi-arid regions. J Atmos Sci 34:1366–1385

Cheng X, An S, Chen J, Li B, Liu Y, Liu S (2007) Spatial relationships among species, above-ground biomass, N, and P in degraded grasslands in Ordos Plateau, northwestern China. J Arid Environ 68:652–667

Daiyuan P, Bouchard A, Legendre P, Gérald D (1998) Influence of edaphic factors on the spatial structure of inland halophytic communities: a case study in China. J Veg Sci 9:797–804

Domingo F, Villagarcía L, Boer MM, Alados-Arboledas L, Puigdefabregas J (2001) Evaluating the long term water balance of arid zone stream bed vegetation using evaporation modelling and hillslope runoff measurements. J Hydrol 243:17–30

Dregne HE (1991) Desert expansion: monitoring and assessment. In: Dregne HE (ed) Desert development, part I. Harwood Academic Publishers, New York, pp 21–32

Dregne HE (1998) Desertification assessment. In: Lal R, Blum WH, Valentine C, Stewart BA (eds) Method of assessment for soil degradation. CRC, New York, pp 441–458

Dunkerley DL (2000) Hydrologic effects of dryland shrubs: defining the spatial extent of modified soil water uptake rates at an Australian desert site. J Arid Environ 45:159–172

He MZ, Zheng JG, Li XR, Qian YL (2007) Environmental factors affecting vegetation composition in the Alxa Plateau, China. J Arid Environ 69:473–489

Huenneke LF, Clason D, Muldavin E (2001) Spatial heterogeneity in Chihuahuan Desert vegetation: implications for sampling methods in semi-arid ecosystems. J Arid Environ 47:257–270

Huerta-Martínez FM, Vázquez-García JA, García-Moya E, López-Mata L, Vaquera-Huerta H (2004) Vegetation ordination at the southern Chihuahuan Desert (San Luis Potosi, Mexico). Plant Ecol 174:79–87

Institute of Soil Sciences, Chinese Academy of Sciences (ISSCAS) (1978) Physical and chemical analysis methods of soils. Shanghai Science Technology Press, Shanghai, pp 7–59 (in Chinese)

Jafari M, Zare Chahoukib MA, Tavilib A, Azarnivandb H, Gh ZahediAmirib (2004) Effective environmental factors in the distribution of vegetation types in Poshtkouh rangelands of Yazd Province (Iran). J Arid Environ 56:627–641

Li SG, Harazono Y, Zhao HL, He ZY, Chang XL, Zhao XY, Zhang TH, Oikawa T (2002) Micrometeorological changes following establishment of artificially established Artemisia vegetation on desertified sandy land in the Horqin Sandy Land, China and their implication in regional environmental change. J Arid Environ 52:101–119

Li FR, Zhang H, Zhang TH, Shirato Y (2003) Variations of sand transportation rates in sandy grasslands along a desertification gradient in northern China. Catena 53:255–272

Li FR, Kang LF, Zhang H, Zhao LY, Shirato Y, Taniyama I (2005) Changes in intensity of wind erosion at different stages of degradation development in grasslands of Inner Mongolia, China. J Arid Environ 62:567–585

Li XR, Jia XH, Dong GR (2006a) Influence of desertification on vegetation pattern variations in the cold semi-arid grasslands of Qinghai-Tibet Plateau, North-west China. J Arid Environ 64:505–522

Li YQ, Zhao HL, Zhao XY, Chen PY (2006b) Biomass energy, carbon and nitrogen stores in different habitats along a desertification gradient in the semiarid Horqin Sandy Land. Arid Land Res Manag 20:43–60

Liu Q, Zhou LH (1996) Primary study on interrelation between plant communities and environmental factors in the north shore of Qinghai Lake. Acta Bot Sin 38:887–894

Liu ZM, Yan QL, Baskin CC, Ma JL (2006) Burial of canopy-stored seeds in the annual psammophyte *Agriophyllum squarrosum* Moq. (Chenopodiaceae) and its ecological significance. Plant Soil 288:71–80

Mabbutt JA (1986) Desertification indicators. Clim Change 9:113–122

Maestre FT, Cortina J (2002) Spatial patterns of surface soil properties and vegetation in a Mediterranean semi-arid steppe. Plant Soil 241:279–291

Maestre FT, Cortina J, Bautista S, Bellot J, Vallejo R (2003) Small-scale environmental heterogeneity and spatiotemporal dynamics of seedling survival in a degraded semiarid ecosystem. Ecosystems 6:630–643

Martinez-Turanzas GA, Coffin DP, Burke IC (1997) Development of microtopography in a semi-arid grassland: effects of disturbance size and soil texture. Plant Soil 191:163–171

Maun MA, Lapierre J (1986) Effects of burial by sand on seed germination and seedling emergence of four dune species. Am J Bot 73:450–455

Milton SJ, Hoffman MT (1994) The application of state-and-transition models to rangeland research and management in arid succulent and semi-arid grassy Karoo, South Africa. S Afr J Sci 11:18–26

Nelson D, Sommers L (1982) Total carbon, organic carbon and organic matter. In: Page AL et al (eds) Methods of soil analysis, part 2, ASA Publication No. 9, 2nd edn edn. ASA and SSSA, Madison, pp 539–577

Nemoto M, Lu XY (1992) Ecological characteristics of *Agriophyllum squarrosum*, a pioneer annual on sand dunes in eastern Inner-Mongolia, China. Ecol Res 7:183–186

Palmer MW (1992) The coexistence of species in fractal landscapes. Am Nat 139:375–397

Puigdefábregas J, Solé A, Gutiérrez L, del Barrio G, Boer M (1999) Scales and processes of water and sediment redistribution in drylands: results from the Rambla Honda field site in SE Spain. Earth Sci Rev 48:39–70

Puignaire FI, Haase P, Puigdefábregas J (1996) Facilitation between higher plant species in a semiarid environment. Ecology 77:1420–1426

Robertson GP, Huston MA, Evans FC, Tiedje JM (1988) Spatial variability in a successional plant community: patterns of nitrogen availability. Ecology 69:1517–1524

Rodríguez Rodríguez A, Mora JL, Arbelo C, Bordon J (2005) Plant succession and soil degradation in desertified areas (Fuerteventura, Canary Islands, Spain). Catena 59:117–131

Rubio JL, Bochet E (1998) Desertification indicators as diagnosis criteria for desertification risk assessment in Europe. J Arid Environ 39:113–120

Sala OE, Lauenroth WK, Golluscio RA (1997) Plant functional types in temperate semi-arid regions. In: Smith TM, Shugart HH, Woodward FI (eds) Plant functional types. Cambridge University Press, Cambridge, pp 217–233

Schlesinger WH, Pilmanis AM (1998) Plant–soil interactions in deserts. Biogeochemistry 42:169–187

Schlesinger WH, Reynolds JF, Cunningham GL, Huenneke LF, Jarrell WM, Virginia RA, Whitford WG (1990) Biological feedbacks in global desertification. Science 247:1043–1048

Schlesinger WH, Raikes JA, Hartley AE, Cross AF (1996) On the spatial pattern of soil nutrients in desert ecosystems. Ecology 77:364–374

Schreiber KF, Yair A, Shachak M (1995) Ecological gradients along slopes of the northern Negev highlands, Israel. In: Blume HP, Berkowicz SM (eds) Arid ecosystems, advances in geoecology, vol 28. Catena, Cremlingen, pp 209–229

Sebastiá MT (2004) Role of topography and soils in grassland structuring at the landscape and community scales. Basic Appl Ecol 5:331–346

Sperry J, Hacke UG (2002) Desert shrub water relations with respect to soil characteristics and plant functional type. Funct Ecol 16:367–378

Su YZ, Zhao HL, Zhang TH, Zhao XY (2004) Soil properties following cultivation and non-grazing of a semiarid sandy grassland in northern China. Soil Till Res 75:27–36

Su YZ, Li YL, Zhao HL (2006) Soil properties and their spatial pattern in a degraded sandy grassland under post-grazing restoration, Inner Mongolia, northern China. Biogeochemistry 79:297–314

Ter Braak CJF (1986) Canonical correspondence analysis: a new eigenvector method for multivariate director gradient analysis. Ecology 67:1167–1179

Ter Braak CJF, Smilauer P (1998) CANOCO releases 4.0 reference manual and user's guide to Canoco for Windows. Microcomputer Power, Ithaca

UNEP (1994) United Nations Convention to Combat Desertification in those countries experiencing serious drought and/or desertification, particularly in Africa. Text with annexes. United Nations Environment Programme for the Convention to Combat Desertification (CCD), Interim Secretariat for the CCD, Geneva, 71p

Verstraete MM, Schwartz SA (1991) Desertification and global change. Vegetatio 91:3–13

Wang T (2000) Land use and sandy desertification in the North China. J Desert Res 20:103–107 (in Chinese with English abstract)

Westoby M (1989) Selective forces exerted by vertebrate herbivores on plants. Trends Ecol Evol 4:115–117

Zhang JY, Zhao HL, Zhang TH, Zhao XY, Drake S (2005) Community succession along a chronosequence of vegetation restoration on sand dunes in Horqin Sandy Land. J Arid Environ 62:555–566

Zhao HL, Zhao XY, Zhang TH, Zhou RL (2005) Desertification processes of sandy rangeland due to over-grazing in semi-arid area, Inner Mongolia, China. J Arid Environ 62:309–319

Zhu ZD, Chen GT (1994) The sandy desertification in China. Science Press, Beijing, pp 7–268 (in Chinese)

Zhu Z, Wang T (1992) Theory and practice on sandy desertification in China (in Chinese). J Quat Sci 2:126–127

Zuo XA, Zhao XY, Zhao HL, Li YQ, Guo YR, Zhao YP (2007) Changes of species diversity and productivity in relation to soil properties in sandy grassland in Horqin Sandy Land. Environ Sci 28:18–24

Zuo XA, Zhao HL, Zhao XY, Guo YR, Li YL, Luo YY (2008) Plant distribution at the mobile dune scale and its relevance to soil properties and topographic features. Environ Geol 54:1111–1200