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Influence of desertification on vegetation pattern variations in the cold semi-arid grasslands of Qinghai-Tibet Plateau, North-west China

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Abstract

In arid and semi-arid grassland, many models hypothesize that desertification leads to the replacement of grassland by shrubland vegetation; however, the theoretical interpretations are open to debate. Therefore, a field study was conducted in the Guinan desertified grassland of the Qinghai-Tibet plateau, North-west China, to test the hypotheses on a regional scale. We used four field sites to represent the four stages of desert development: slight, moderate, severe and very severe. A total of 40 quadrates were investigated in each site. Plant coverage, above-ground biomass, species richness and life-form were recorded; species diversity was calculated using the Simpson index and soil parameters were also measured. Our results indicate that the proportion of silt decreases from 12% in the slight stage to 1% in the very severe stage, clay from 71% to 42% and sand from 17% to 93%. Soil water-holding capacity clearly decreases from the slight to the very severe stage. Soil organic matter (OM) is also reduced with desert development, which leads to destruction of the stability of soil physical structure and nutrient content, such as progressive N, P and K loss in surface and subsoil layers. In response to changes in soil properties, vegetation altered as regards species composition, species diversity, coverage, structure and life-form. Consequently, with desert development, herbaceous species, especially grasses, were lost from the community composition and replaced by xerophytic shrubs or semi-shrubs. Finally, psammophytic annual plants-dominated vegetation composition, while shrub maintained a low coverage. Although our results partially support previous hypotheses at the regional scale, it is considered that, apart from soil texture, soil OM and

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nutrients are the main factors mediating the dominance balance between shrub and herbaceous species.

Keywords: Desertification; Vegetation pattern; Soil texture; Qinghai-Tibet plateau

1. Introduction

Desertification is generally understood to refer to land degradation in arid, semi-arid and dry semi-humid climatic zones (UNEP, 1992). It involves five principal processes: vegetation degradation, water erosion, wind erosion, salinization and waterlogging, and soil crusting and compaction (Dregne, 1998). Amongst these, soil degradation means the displacement of soil material driven by water and wind erosion, and internal deterioration caused by physical and chemical processes, such as salinization and nutrient loss (Takar et al., 1990; Zobeck, 1991). Vegetation degradation includes the loss of coverage and biomass, as well as compositional changes, such as replacement of native by exotic species (Mouat and Hutchinson, 1995). Some hypotheses for desertification in semi-arid grassland 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; Havstad et al., 2000). Thus, desertification leads to changes in vegetation pattern and structure: changes from grassland to shrubland due to increasing spatial and temporal heterogeneity of water, nutrient and other soil properties (Dunkerley, 2000; Sperry and Hacke, 2002). The importance of soil texture in these changes has been clearly established (Lauenroth and Milchunas, 1991), namely, the balance between the dominance of woody and herbaceous species is mediated by soil texture, in addition to climatic factors (Dodd et al., 2002). Most soil types are dominated by grass and only coarse-textured soil supports the dominance of shrub species (Sala et al., 1997). However, this interpretation lacks sufficient evidence according to other recent studies (Jeltsch et al., 2000; Wezel et al., 2000; Moleele and Chanda, 2003; Ward, 2003). Additionally, most of these studies have been carried out in North America, African savannas, Australia and arid regions in other countries. While China is one of the most desertified countries in the world, few studies have been reported from China and central Asia (Li et al., 2004), in particular, from the cold semi-arid grassland of the Qinghai-Tibet plateau. According to one recent study, the mean annual rate of desertification in China has risen from approximate 1142 km^2 in the 1960s to 2460 km^2 in the 1990s (Wang, 2000). Apart from biophysical causes, related to climatic, edaphic, topographic and geological features, an anthropogenic cause, stemming from inappropriate human activities, such as overgrazing, has also resulted in the grassland desertification in China (Zhu and Chen, 1994). Even so, before knowledge of desertified processes can be adequately understood, the relationship between the variation in soil properties and the concomitant changes in vegetation must be clarified. Such enhanced understanding may contribute to desertification control and the restoration of degraded grassland. Thus, the aim of the present study was to test existing hypotheses for grassland desertification. In particular, the objectives are: (1) to explore how vegetation responds in species composition, life-form and pattern to changes in soil properties, (2) to establish the main factors influencing vegetation changes and (3) to enhance our understanding of the restoration mechanism of grassland degradation in a cold semi-arid region.

2. Materials and methods

2.1. Study area

The study was conducted in the Guinan Grassland, Qinghai Province, located in the eastern part of the Qinghai-Tibet plateau (35°42′N and 100°50′E), with an elevation of 4339 m (Fig. 1). This grassland belongs to a typical cold desertified steppe zone (Dong et al., 1993; Lu, 1995). The mean annual precipitation in the grassland is 367.9 mm (1970–2002), falling mainly from June to September. The annual average temperature is 0.88 °C; the highest temperature is 11.98 °C in July and the lowest is −11.98 °C in January (Fig. 2). Evaporation averages 1525.4 mm yearly. Sandstorms and dust suspension occur on about 174 days per year. Wind speed is greatest during late spring (April–May), with an average of $3.5\,\mathrm{m\,s^{-1}}$, predominantly from the north-west. The dominant native plants are *Stipa krylovii*, *Orinus thoroldii*, *Artemisia frigida* in undegraded steppe, and *Stipa breviflora*, *Carex stemophylla*, *Sibbaldia adpressa* and *Leymus secalimus* in desertified steppe. The main soil types are chestnut soil (undegraded steppe), brown soil and aeolian sandy soil (degraded steppe) (Xun and Li, 1987; Dong et al., 1993).

2.2. Desertification grades

Desertification in the Guinan grassland falls into four grades, on the criteria described by Zhu (1981), Dong et al. (1993) and Dregne (1994), namely, slight or potential, moderate, severe and very severe desertification (Table 1). Within the total study area, the proportions of these four grades are, respectively, 67.74% (A), 18.36% (B), 3.43% (C) and 10.37% (D) (Fig. 1) (Jin et al., 1989a,b; Dong et al., 1993).

Slightly desertified grasslands (A) are characterized by fixed sand (Table 1), including fixed sand dunes and grazing enclosures that were established in 1950 and have relatively light grazing disturbance (1 month of grazing occurred in autumn once a year). The standing carrying capacity for this grade of grassland for livestock is 2% more than its theoretic carry capacity (the theoretical carry capacity for the Guinan grassland is 0.35 sheep units $\mathrm{hm^{-2}}$) (Dong et al., 1993; Su, 1997). The herbaceous biomass of this grade of grassland has decreased 22.4% in comparison with that of original vegetation (undegraded grassland), and the dominant species in vegetation composition consisted of *Stipa krylovii*, *Orinus kokonorica* and *Stipa*

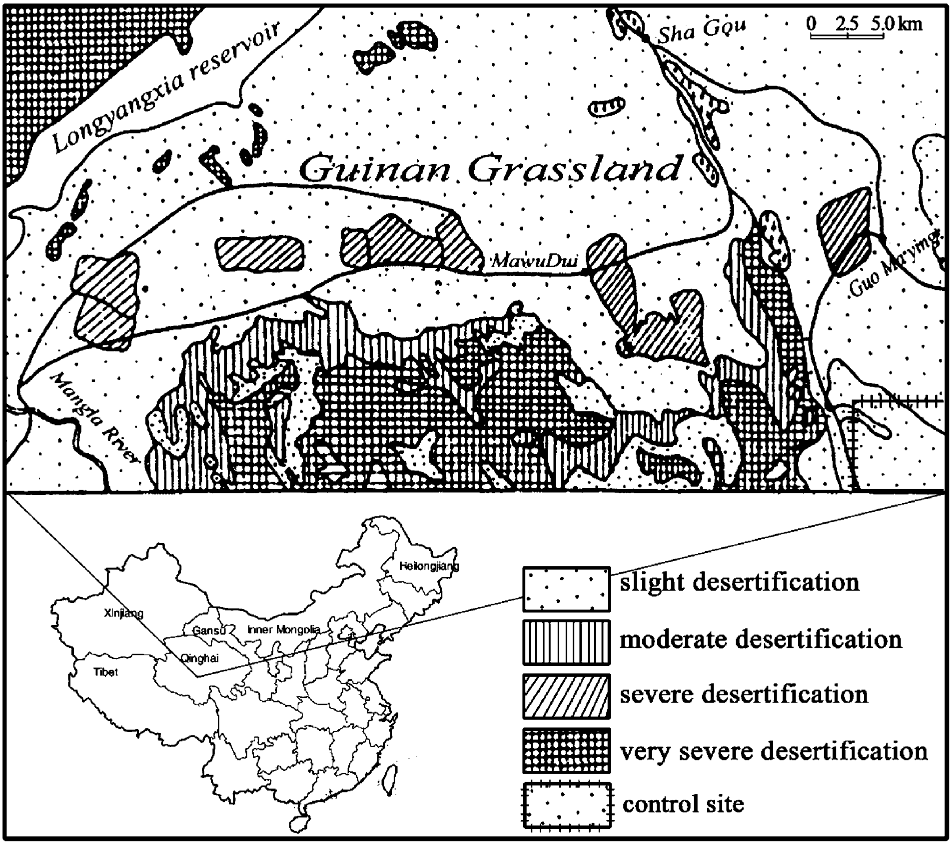

Fig. 1. Distribution of desertified areas in the Guinan grassland.

breviflora, etc. Vegetation coverage is more than 60%. The area of mobile sand occupies 1–2% of the total area of this grade (Table 1).

Moderate desertified grasslands (B) are characterized by semi-fixed sand, including semi-fixed sand dunes, plain sand areas or desertified fields. The herbaceous biomass of this grade of grassland has decreased 48.6% in comparison with that of original vegetation. Numerous psammophytes, such as *Orinus kokonorica*, *Achnatherum inebrians, Agropyron criststum*, have gradually become dominant species in vegetation communities, and some semi-shrubs and shrubs, such as *Artemisia arenaria* and *Caragana stenophylla*, have also been established in the communities. Vegetation coverage is between 30% and 60%, and the standing carrying capacity is 10–15% more than the theoretical carry capacity. The management approach for this grassland involves rotational grazing (grazing occurs only in summer). Soil wind erosion can be found on windward slopes of semi-fixed sand dunes. The area of mobile sand ranges from 10% to 15% of the total area of this grade.

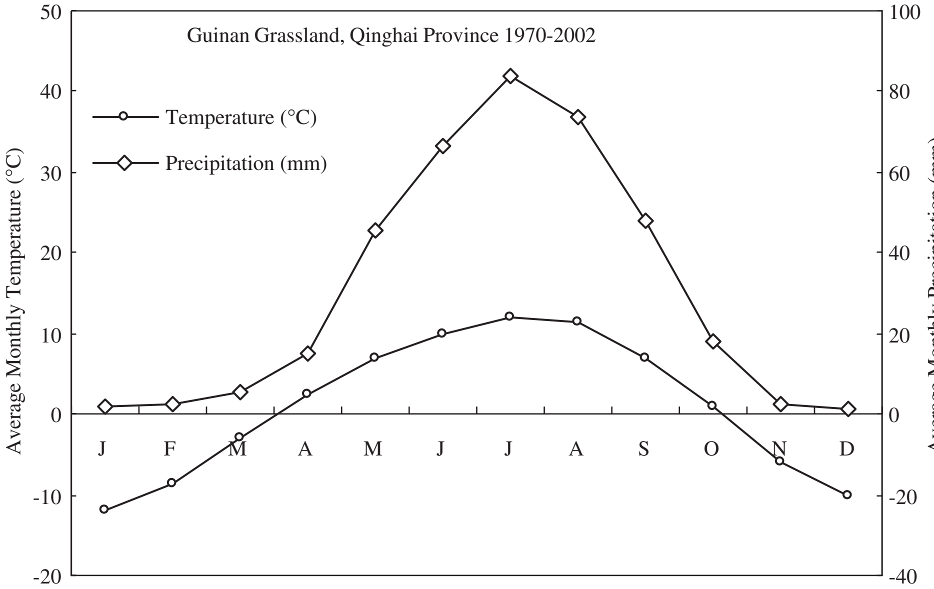

Fig. 2. Eco-climate of the Guinan grassland, Qinghai Province.

Severe desertified grasslands (C) are characterized by semi-shifting sand dunes and plain sand areas, with intensified wind erosion on the soil surface. Few plant species from the original vegetation can be found; the dominant species are *Leymus secalimus*, *Artemisia arenaria*, *Oxytropis acciphylla*, *Caragana stenophylla*, etc., and vegetation coverage ranges from 10% to 30%. Vegetation biomass of this grade of grassland has decreased 80.2% in comparison with that of the original vegetation (Jin et al., 1989a,b). Standing carrying capacity is 30–35% more than the theoretical carry capacity and mobile sand occupies 30–50% of the total area of this grade of grassland. Apparently, no effort has been used to manage the grassland and the grazing situation is chaotic.

Very severe desertified grasslands (D) are characterized by evident sand-cover and large areas of mobile sand; the mobile sand area exceeds 50% of the total area for this grade of grassland. The dominant plant species are *Artemisia arenaria, Oxtropis acciphylla*, as well as *Achnatherum splendens* and *Agriophyllum squarrosum*. This grade of grassland endured long-term overgrazing pressure; the standing carrying capacity is 45–50% more than the theoretical carry capacity (Table 1).

2.3. Vegetation survey

Quadrates in the vegetation survey were $10 \times 10\,m^2$ for shrubs and $1 \times 1\,m^2$ for herbs. A total of 200 quadrats (100 for shrubs and 100 for herbs) were assigned to investigate plant communities in different desertification stages. On average, 40 quadrats (20 for shrubs and 20 for herbs) were distributed in each grade of grassland,

Table 1
Degree of grassland desertification and features during different desertification stages of the Guinan Grassland, Qinghai province, North-west China

Stages of desertification	Sites (area hm^2)	Features of landforms (proportion of mobile dune area %)	Dominant species	Species richness (number per $100\,m^{-2}$)	Vegetation coverage (%, mean ± S. E.)	Simpson index S (mean ± S. E.)	Herbaceous biomass ($g\,m^{-2}$) (mean ± S.E.)	Management and use state
Original vegetation/no desertification	Control (1 0 0)	Typical cold steppe (0%)	*Stipa krylovii*, *Orinus kokonorica*, *Leymus secalimus*, *Artemisia frigida*	24 ± 1.76a	> 90 (91 ± 7.24a)	0.6051 ± 0.0935a	126.0 ± 14.6a	No grazing disturbance, enclosed (50 years), theoretic carry capacity is 0.35 sheep units per hm^{-2}
Slight stage	A (53 714.4)	Fixed sandland, fixed sanddunes, semi-fixed sandland (1–2%)	*Stipa krylovii*, *Orinus kokonorica*, *Stipa breviflora*, *Stipa purpurea*, *Leymus secalimus*, *Carex stemophylla*, *Agropyron cristatum*, *Iris lacteal* var. *chinensis*, *Agropyron cristatum.*	23 ± 2.13a	> 60 (74.46 ± 15.18b)	0.6445 ± 0.0757a	97.8 ± 11.6b	Enclosed (50 years), slight seasonal grazing, standing carrying capacity is 0.37 sheep units per hm^{-2}
Moderate stage	B (14 564.6)	Semi-fixed sanddunes, abandoned field, flat sandland and aeolian depression (10–15%)	*Orinus kokonorica*, *Achnatherum inebrians*, *Agropyron cristatum*, *Poa annua*, *Careoc stemophylla*, *Stipa breviflora*. *Stellera chamaejasme*	20 ± 3.27b	30–60 (43.00 ± 8.69c)	0.4768 ± 0.1142b	64.8 ± 7.24c	Rotational grazing, standing carrying capacity is 0.45–0.50 sheep units per hm^{-2}
Severe stage	C (2720.9)	The original soil surface has been destroyed by erosion and sand cover, semi-shifting sanddunes and flat sandland (30–50%)	*Leymus secalimus*, *Artemisia arenaria*, *Oxytropis aciphylla*, *Caragana stenophylla*, *Agriophyllum squarrosum*, *Stellera chamaejasme*	11 ± 3.11c	10–30 (24.38 ± 7.76d)	0.3769 ± 0.0438b	24.9 ± 9.64d	Strong overgrazing, standing carrying capacity is 0.65–0.70 sheep units per hm^{-2}
Very severe stage	D (8226.3)	The most part of land was covered by shifting sanddunes, severe erosion (> 50%)	*Achnatherum splendens*, *Artemisia arenaria*, *Agriophyllum squarrosum*	6 ± 2.23d	< 10 (7.80 ± 3.03e)	0.2568 ± 0.0665c	7.1 ± 3.2e	Strong overgrazing, standing carrying capacity is 0.80–0.85 sheep units per hm^{-2}

Values with different letters are significantly different among different sites ($p < 0.01$).

the surplus 40 quadrats were located in the control site for measuring the herbaceous biomass of the original grassland (Table 1 and Fig. 1). The control site was an undegraded grassland of 100 hm^2, where the grassland was enclosed for 50 years and grazing prohibited (Shao et al., 1988).

For each quadrat, species number, abundance, height, shrub coverage, herbaceous coverage and total community coverage are recorded. *Importance value* of species ($IV =$ relative height + relative cover) were calculated with the equation, described by Dong et al. (1993); the *Simpson index* ($S = 1 - \sum p_i^2$, where p_i is the relative importance value (IV) of species i) was used to measure plant species diversity (Li et al., 2000). Plants were clipped by species in each quadrat of size 1 m^2 and the fresh above-ground biomass for all herbaceous species was weighed.

2.4. Soil sampling

Soil samples were taken at depths of 0–20 cm, 4 days after a rainfall event so that intact cores could be extracted. Three replicate samples were taken in each quadrat, then dried at 105 °C in the laboratory and, lastly, crushed and sieved through a 2 mm screen. Particle size was determined by the pipette method (Loveland and Whalley, 2001). pH was determined with a soil suspension of soil–water, in the ratio of 1:5, using a calibrated pH meter (PHS-4, Jiangsu Manufactory of Electrical Analysis Instruments, Jiangying, China). Soil organic matter (OM) was measured by the $K_2Cr_2O_7$ method, as described by the Agriculture Chemistry Speciality Council, Soil Science Society of China (1983). Electrical conductivity (EC) was measured by a hand-held conductivity meter (Cole–Parmer Instruments Company, IL, USA). Total N was measured by a Kjeltec System 1026 distilling unit (Tecator AB, Höganäs, Sweden). Phosphorus and potassium were measured by the standard methods for observation and analysis of the Chinese Ecosystem Research Network (CERN) (Liu, 1996). Soil–water characteristic curves were determined by a pressure (15 bar) ceramic plate extractor (CAT-1600; Soil Moisture Equipment Company, Santa Barbara, CA, USA).

2.5. Statistical analysis

Differences in plant species richness, cover, biomass and soil parameters among the different degraded grasslands were analysed using variance analysis (one-way ANOVA). Results were checked by Tukey's test. These procedures were performed on Windows-based SPSS 10th edition software (SPSS, Chicago, IL, USA).

3. Results

3.1. Variation of vegetation pattern in the process of grassland desertification

Differences in plant species richness for the four stages of desert development are obvious (Table 1, $p < 0.01$), but unclear between the slight stage and original vegetation ($p > 0.01$). Similarly, there is no significant difference in the plant diversity index (S) between the slight and original vegetation, nor between the moderate and severe stage ($p > 0.01$), but there is an apparent decreasing tendency in species diversity for the positive developmental processes of desertification (Table 1). For vegetation coverage and herbaceous biomass, significant differences are found among the grasslands at different desertification stages, e.g. vegetation coverage decreases remarkably from 91 ± 7.24% for the original vegetation to 7.80 ± 3.03% for the very severe desertified stage; simultaneously the biomass of herbaceous species decreases from 126.0 ± 14.6% to 7.1 ± 3.2 $\mathrm{g\,m^{-2}}$.

Table 2 shows that the importance values (IV) for dominant species in vegetation communities, such as *Stipa krylovii*, *Leymus secalinus*, *Artemisia frigida* and *Careoc stemophylla*, decrease with the positive development of desertification. Whereas, IV values of some psammophytes and indicator species, such as *Artemisia arenaria*, *Oxytropis aciphylla*, *Caragana stenophylla* and *Stellera chamaejasme*, *Achnatherum inebrians*, increase during this process. Thus, shrub and semi-shrub species gradually established themselves in community composition with desert development.

There are also obvious differences in life-form composition among plant communities during the different desertification stages (Table 3). Phanerohytes and therophytes gradually occupy a greater proportion of the life-form composition from the original vegetation to plant communities in the very severe desertification stage, but the dominance of cryptophytes gradually weakened with the development of desertification. Intuitively, life-form composition is closely associated with changes in plant community structure and landform. On the whole, data in Tables 2 and 3 show that the vegetation pattern evolution in the process of grassland

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

	Desertification stages				
	Control	Slight	Moderate	Severe	Very severe
Stipa krylovii	0.5063	0.4841	0.1483	—	—
Stipa breviflora	0.1237	0.1461	0.2812	0.0241	—
Agropyron cristatum	—	0.1162	0.3412	0.0361	0.0112
Orinus kokonorica	—	—	0.1243	0.1222	0.0132
Leymus secalinus	0.2214	0.1146	0.0672	0.0130	—
Careoc stemophylla	0.1266	0.1082	0.1634	0.0246	—
Potentilla bifurca	—	0.0244	0.0643	—	—
Poa annua	0.1143	0.0861	0.0532	—	—
Stellera chamaejasme	—	—	0.0121	0.2431	—
Achnatherum inebrians	—	—	0.0324	0.1421	0.1426
Artemisia frigida	0.2413	0.0723	—	—	—
Artemisia arenaria	—	—	—	0.1052	0.3131
Oxytropis aciphylla	—	—	—	0.064	0.2452
Caragana stenophylla	—	—	—	0.031	0.2142

Table 3
Characteristics of life-form composition during different desertification stages of the Guinan grassland

Desertified stages	Phanerophytes (%)	Chamaephytes (%)	Hemicryptophytes (%)	Cryptophytes (%)	Therophytes (%)
Control	—	—	6.4	93.6	—
Slight	—	1.0	8.6	90.4	—
Moderate	—	4.6	10.3	85.3	—
Severe	14.8	9.9	31.4	38.5	5.4
Very severe	30.6	15.5	13.8	20.4	19.7

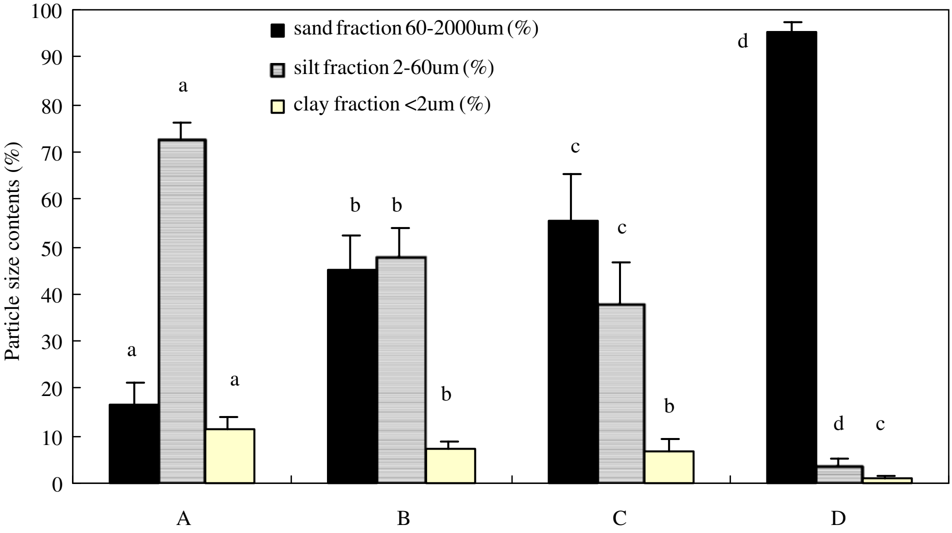

Fig. 3. Soil particle-size distribution at different stages of desertification in the Guinan grassland (mean ± S.E.; values with different letters are significantly different in different sites).

desertification follows the pattern of long-lived grass species being replaced by xerophytic shrub, semi-shrub species and some annual psammophilous plants.

3.2. Variation of soil physiochemical features in grassland desertification

Along with the development of grassland desertification, soil granularity changes remarkably (Fig. 3), which is shown by the significant differences among quadrates at different desertification stages ($p<0.01$). Generally, with the development of desertification, soil texture becomes coarser, e.g. silt content decreases from 72.41 ± 3.89% in the slight stage to 3.54 ± 1.73% in the very severe stage and clay content from 11.19 ± 2.72% to 0.89 ± 0.59%, whereas sand content increases from 16.42 ± 4.74% to 95.57 ± 1.77%.

Fig. 4 shows the relationship between soil clay content and OM, from which it can be seen that the percentage of clay in topsoil is highly positively correlated with the percentage of soil OM. The figure also implies that soil OM decreases with the development of desertification, resulting in an apparent decrease in soil clay during this process.

Soil water characteristic curves indicate that the water-holding capacity of topsoil decreases from the slight desertification stage to the more deteriorated stages (Fig. 5). This finding suggests that the development of grassland desertification might contribute to increasing infiltration of rainfall from topsoil to deeper layers.

Soil pH is one of the important indicators of soil. Significant differences were found among the different desertification stages ($F = 4.611 > F_{0.05} = 4.52, p < 0.05$) (Fig. 6); an exception was between the slight and moderate stage ($p = 0.369 > 0.05$) (Table 4). Nevertheless, there is still an increasing pH tendency with the development of grassland desertification in a cold region. By contrast, soil EC shows a clear decreasing tendency with the development of desertification, e.g. it decreases from $144.13 \pm 28.66\,\mathrm{S\,m^{-1}}$ in the slight stage to $60.37 \pm 8.10\,\mathrm{S\,m^{-1}}$ in the very severe stage (Fig. 6), but no significant differences are found among the desertification stages ($p > 0.05$), except between the slight and very severe stage. The slight decrease in soil

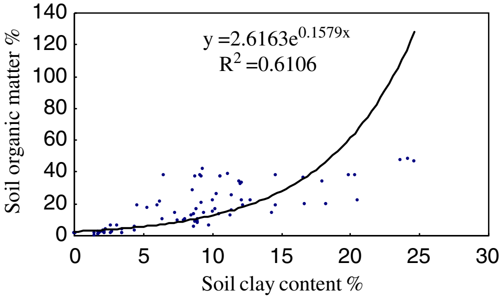

Fig. 4. Relationship between soil clay content and organic matter.

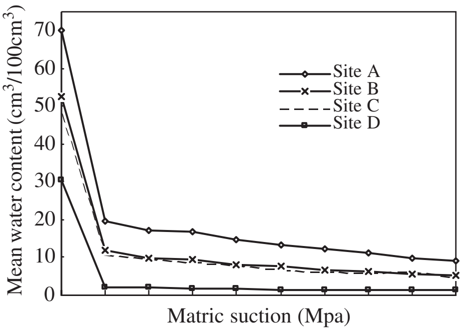

Fig. 5. Soil–water characteristic curve at different stages of desertification in the Guinan grassland.

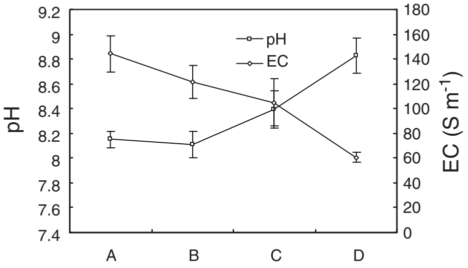

Fig. 6. Changes in soil pH value and electric conductivity at different stages of desertification in the Guinan grassland (mean ± S.E.).

salt content in topsoil (0–20 cm depth) and surface soils with desert development results from the physical process of desertification, in particular, wind erosion promotes accumulation of sands on the soil surface, leading to a reduction in surface soil evaporation, so the salt rising to the topsoil is inhibited.

3.3. Variation of soil nutrients in grassland desertification

Soil OM content varies greatly with the development of desertification. Fig. 7 shows that soil OM changed from a high content ($37.49 \pm 10.06\,\mathrm{g\,m^{-2}}$) in the slight stage to a very low content ($1.74 \pm 0.36\,\mathrm{g\,m^{-2}}$) in the very severe stage: a reduction of 92.8%. Although there is a significant difference in soil OM between the slight and severe stage ($p < 0.01$), there is no significant difference between the severe and very severe stage (Table 4), which means that most of the OM in topsoil has been lost during the severe stage of desertification.

Similar to soil OM, the change of soil total N is clearly related to the development of desertification (Fig. 7). There is also a significant difference in soil total N between the slight and severe stage ($p < 0.01$) and no significant difference between the severe and very severe stage. Soil total N reaches a very low value by the end of the severe stage of desertification. In comparison to the change in soil total N, the change in soil P is relatively unclear (Fig. 7 and Table 4) in the process of desertification, and no significant difference was found between the slight and moderate stage ($p > 0.05$) or between the moderate and severe stage ($p > 0.05$). Regarding K content in topsoil, significant differences were found between the above two pair of stages. Similar results have also been reported in several studies from arid and semi-arid regions (Jin et al., 1989a,b).

3.4. Relationship between vegetation and soil properties

Correlation analyses show that there are close relationships between vegetation coverage and soil parameters, such as soil OM ($r = 0.79$), total N ($r = 0.79$), K ($r = 0.79$) and silt ($r = 0.67$) (Table 5), which suggests that soil nutrient and OM are the major factors in controlling vegetation coverage. Table 5 also shows that

Table 4
Comparison of soil properties and vegetation parameters among four desertification stages

		A			B			C				A			B			C		
		Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay		N	P	K	N	P	K	N	P	K
	Sand	0.03*									N	0.00**								
B	Silt		0.04*								P		0.10^{NS}							
	Clay			0.04*							K			0.05*						
	Sand	0.00**			0.03*						N	0.00**			0.00**					
C	Silt		0.00**			0.23^{NS}					P		0.01**			0.18^{NS}				
	Clay			0.01**			0.53^{NS}				K			0.00**			0.21^{NS}			
	Sand	0.00**			0.00**			0.01**			N	0.00**			0.00**			0.12*		
D	Silt		0.00**			0.00**			0.01**		P		0.00**			0.00**			0.05*	
	Clay			0.00**			0.01**			0.02**	K			0.00**			0.00**			0.04*
		OM	pH	EC	OM	pH	EC	OM	pH	EC		Cover	Biomass	*S*	Cover	Biomass	*S*	Cover	Biomass	*S*
	OM	0.00**									Cover	0.00**								
B	pH		0.37^{NS}								Biomass		0.00**							
	EC			0.53^{NS}							*S*			0.32^{NS}						
	OM	0.00**			0.00**						Cover	0.00**			0.01**					
C	pH		0.00**			0.04*					Biomass		0.00**			0.01**				
	EC			0.11^{NS}			0.34^{NS}				*S*			0.00**			0.04*			
	OM	0.00**			0.00**			0.25^{NS}			Cover	0.00**			0.00**			0.00**		
D	pH		0.00**			0.00**			0.00**		Biomass		0.00**			0.00**			0.05^{NS}	
	EC			0.00**			0.010*			0.08^{NS}	*S*			0.00**			0.00**			0.21**

A, B, C and D represented different desertified stages, respectively.
NS: No significant difference.
*The mean difference is significant at the 0.05 level ($p<0.05$).
**The mean difference is significant at the 0.01 level ($p<0.01$).

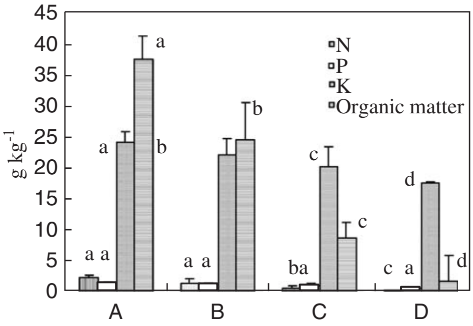

Fig. 7. Soil nutrient changes at different stages of desertification in the Guinan grassland (mean ± S.E.; values with different letters are significantly different among different sites).

Table 5
Correlation coefficients between vegetation cover, biomass, Simpson index (*S*) and soil properties

	pH	N	P	K	OM	EC	Clay	Silt	Sand	Cover	Biomass
N	−0.69**										
P	−0.55*	0.86**									
K	−0.57**	0.89**	0.89**								
OM	−0.67**	0.98**	0.99**	0.88**							
EC	−0.56*	0.58*	0.59**	0.66**	0.57*						
Clay	−0.61**	0.82**	0.82**	0.85**	0.78**	0.61**					
Silt	−0.71**	0.88**	0.88**	0.92**	0.85**	0.74**	0.84**				
Sand	0.70**	−0.89**	−0.89**	−0.92**	−0.86**	−0.73**	−0.88**	−0.99**			
Cover	−0.67**	0.79**	0.79**	0.65**	0.79**	0.55*	0.57**	0.67**	−0.67**		
Biomass	−0.61**	0.74**	0.74**	0.62**	0.73**	0.52*	0.58**	0.61**	−0.62**	0.95*	
S	−0.57*	0.57**	0.57**	0.39*	0.56**	0.15	0.48*	0.48**	−0.49**	0.57*	0.55*

**Correlation is significant at the 0.01 level (two-tailed).
*Correlation is significant at the 0.05 level (two-tailed).

herbaceous biomass and species diversity are more closely correlated to OM, total N, P, K and soil silt content than to soil pH and EC, and are even negatively correlated to the sand content in soil.

4. Discussion

The conceptual model presented by Sala et al. (1997) hypothesizes that the dominance of shrubs or grasses is related to soil texture, since soil texture plays a significant role in regulating vegetation pattern, including vegetation composition, functional group and structure. Burke et al. (1990) also found that the soil clay content was positively correlated with total soil OM across large regions of the Great

Plains of North America. In addition, many other simulation models prove that soil texture controls the dynamics of soil OM, including OM formation and decomposition (Parton et al., 1988; Raich et al., 1991; Rasetter et al., 1991; Connin et al., 1997).

The influence of soil texture change on the life-form composition of plant communities has been demonstrated in numerous studies, e.g. woody species encroachment, making soil texture coarse, is a recognized problem in arid and semi-arid regions (Palmer and Van Rooyen, 1997). Walter (1979) has put forward a simple model to explain the distributing pattern of grassland with woody plants, in which grasses with dense shallow-rooting systems utilize water resources close to the surface, while deep-rooted woody plants use the water in deeper soil. This model has been used to forecast the dynamics of woody and herbaceous vegetation in semi-arid savanna ecosystems (Walker et al., 1981; Walker and Noy-Meir, 1982). However, recent research from African savannas considered that the above explanations are inadequate or even wrong in many situations (Ward, 2000, 2003). So, some new models and theories, such as the disturbance model (Higgins et al., 2000), patch-dynamic model (Ward, 2003) and ecological buffering mechanisms (Jeltsch et al., 2000) are used to explain the reason for bush encroachment in the savanna ecosystem. These models emphasize the effects of disturbance (e.g. grazing and fire), climatic factors (rainfall and drought) and resource heterogeneity (soil water and nutrients) on the competitive advantages of both bush and grasses. In addition, the positive (Stuart-Hill et al., 1987; Belsky et al., 1989; Smit and Swart, 1994; Tongway and Ludwig, 1994) and negative influences of woody species (Wu et al., 1985; Smit and Rethman, 1998, 2000) on herbaceous plants have been widely reported. Here, it is worthy to note that the savanna ecosystem differs from the grassland ecosystem of the cold temperate zone. Instead of relatively high tree cover, shrub species occur in plant communities of the latter during the desertification process.

According to research by Chinese ecologists, the occurrence of desertification in the cold semi-arid grasslands of the Qinghai-Tibet Plateau can be explained by the following model (Shao et al., 1988; Dong et al., 1993). The main driving force of grassland desertification is wind erosion. Commonly, the grasslands in this region are characterized by a great number of rodent burrows, vehicle tracks and over-stocking management (overgrazing). These sites are where wind erosion starts, and are then gradually extended by strong winds. Desertification processes cannot only promote changes in soil texture, but also lead to the burial phenomena. Sand burial is an environmental stress factor commonly encountered in arid and semi-arid desertified grasslands (Maun and Lapierre, 1986; Brown, 1997). The tolerance of plant species and the general physiological responses of plants to different degrees of sand burial have been extensively studies (Zhang and Maun, 1992). Some studies found that shrub species have more tolerance in adapting to coarse soil texture and sand burial in comparison to herbaceous species (Li, 2000). Changes of water-holding capacity of topsoil become unfavorable for the survival of herbaceous species (Xun, 2001), but some burial-tolerant shrubs, such as *Caragana stenophylla*, *Oxytropis aciphylla* and *Artemisia arenaria*, can increase the above-ground components, including height and number.

Desertification changes soil properties; in particular, soil OM decreases remarkably. Apart from wind erosion, the retreat of herbaceous species from vegetation composition is also the reason for the soil OM decrease. Herbaceous litter is the main source of soil OM because it is easier decomposed than that of shrub species. Additionally, the herbaceous root system can improve soil structure and water, fertility, soil air and temperature conditions, so its contribution to soil OM is greater than that of shrub species (Xun, 2001).

As emphasized by West and Skujins (1978), Skujins (1981), West (1991), Day and Ludeke (1993) and Xie and Steinberger (2001), soil N is one of the major growth-limiting resources in arid and semi-arid environments. Berg et al. (1997) pointed out that, after water, soil N is usually the limiting factor in herbaceous production of grassland. Dregne (1998) indicated that N and P are the most common limiting biological elements in desert ecosystems. Nevertheless, in comparison to other soil parameters, soil OM has a relatively close correlation with vegetation coverage, biomass and Simpson index. So, it might explain the link of vegetation with soil in the desertification processes. Desertification leads to soil OM loss, soil nutrient reduction and topsoil texture destruction. Finally, sands are acceleratively accumulated on topsoil, and soil silt and clay reduced further. The dominant herbaceous species in the original vegetation are replaced by shrub and semi-shrub species.

The desertification process of grassland involves a reduction of herbaceous plant coverage and an increase of shrub biomass. However, the absolute biomass of these shrubs is always low or unavailable to domestic herbivores, leading to over-stocking or overgrazing because the carrying capacity of the grassland is reduced, which, in turn, accelerates the development of desertification (Wang, 2000).

5. Conclusions

The occurrence of desertification in cold semi-arid grassland results in soil property changes, e.g. coarsened soil texture, exhausted organic matter (OM), depleted nutrient and increased soil pH. Changes in soil properties are strongly relate to vegetation pattern, including coverage, richness, diversity and biomass. Desertification promotes changes in the vegetation pattern, e.g. shrub species replace herbaceous species in vegetation composition. Nevertheless, it is considered that, besides soil texture, soil OM and nutrients are the main factors mediating the dominance balance between shrubs vs. herbaceous species in the cold semi-arid grasslands of the Qinghai-Tibet Plateau.

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