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Vegetation coverage, species richness, and dune stability in the southern part of Gurbantüggüt Desert

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Abstract This study investigated the relationship between vegetation coverage, species richness, and environmental factors, and also analyzed the relationship between vegetation coverage, species richness, and dune stability in different terrains, in the southern part of Gurbantüggüt Desert in China. The results showed that the order of vegetation coverage and species richness was greatest in middle areas, followed by the eastern areas, with the western areas being sparse. On a large scale, precipitation from April to June determined the amount of vegetation coverage. On a small scale, vegetation coverage was influenced by the type of terrain and the water and salt content in soils. Species richness of vegetation was determined by soil water and salt content on both the large and small scales. There were also remarkable differences in relative wind erosion among the different terrains and their order was: crest, slope, and inter-dune in descending order. The correlations between wind erosion and vegetation coverage and species richness were influenced by the type of terrain. Furthermore, there were significant correlations between wind erosion and vegetation coverage and species richness in dune slopes and crests. There was, however, no significant correlation between wind erosion and vegetation coverage and species richness in inter-dune sites. Vegetation coverage was the dominant factor influencing wind erosion in both slopes and crests. Species richness may have an impact on wind erosion through vegetation coverage in both slopes and crests. These

results suggest that the effect of terrain type should be fully considered during the establishment of vegetation cover in the desert.

Keywords Southern Gurbantüggüt Desert · Coverage · Species richness · Dune stability

Introduction

A plant community is the product of an interaction between plants and the environment. The spatial distribution of the plant community is influenced by both environmental and spatial factors (Borcard et al. 1992). The relationship between the vegetation and environmental factors in the Gurbantüggüt Desert has recently been explored in several studies: these showed that the main factors causing vegetation variation were the physical and chemical properties of soils, the type of terrain, and the underground water level (Butler et al. 1986; Flowers 1975; Cantero et al. 1998; Requena et al. 2001; Qian et al. 2007, 2008; Stavi et al. 2008; Sang 2009). However, the relationship between vegetation coverage, species richness, and environmental factors has not been investigated. Coverage and species richness are two important characteristics of vegetation, which are influenced by environmental factors, and which exhibit spatial heterogeneity. The Gurbantüggüt Desert is the largest stable to semi-stable desert in China. Its stability is maintained by high vegetation coverage and species richness (Wang et al. 2003; Wasson and Nanninga 1986). Current studies show that as vegetation coverage increases, wind erosion decreases. When vegetation coverage reaches 35–40%, almost no wind erosion occurs (Wasson and Nanninga 1986; Wang et al. 2003). However, there are multiple factors that influence wind erosion in addition to vegetation. The type of terrain, soil properties, and the roughness of the soil surface are also important factors that influence wind erosion (Lu and Dong 2006; He et al. 2008). Therefore, further studies are needed to investigate wind erosion in

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different terrains in the southern Gurbantüggüt Desert. The questions addressed in this study are: (1) what are the main environmental factors that influence vegetation coverage and species richness in the southern region of the Gurbantüggüt Desert? and (2) what are the relationships between vegetation coverage, species richness, and wind erosion? From the results, we expect to provide recommendations for vegetation recovery in different terrains and to identify factors that cause the formation of stable or semi-stable desert.

Materials and methods

Description of the study sites

The Gurbantüggüt Desert is the second largest desert in China, with an area of 48,800 km². It has an arid climate with an average annual temperature of 5–5.7°C, evaporation of 2,000–2,800 mm, strong winds for 25–77 days of the year, wind velocity of 2–3.6 m/s, precipitation of 80–190 mm, sunlight hours of 2,700–3,050 h, and annual precipitation from April to June of 29–58 mm (annual precipitation from April to June was based on the years from 1999 to 2008, other climate data was based on the years 1979–2008). Climate data comes from weather station sites of the state-owned farms. The farms where the sampling sites were located ran deeply into the desert, each sampling sites was 10–20 km from the weather station). Unlike most other arid zones, this area has an average annual snow cover period of about 95–110 days, beginning in late November and ending in mid-March of the following year. The predominant soil is stable or semi-stable aeolian sand followed by saline-alkaline, and gravel soil. Stable or semi-stable dunes account for 96% of the total area of the desert. Psammophyte and drought-resistant plants are the main plants in the desert.

The areas included in this study were located at 44°17.322′–45°01.681′N, 83°12.079′–90°02.541′E. A total of 27 sites were established in the southern Gurbantüggüt Desert in May 2008 (Fig. 1). Sampling sites numbered 1, 4, 7, 10, 13, 16, 21, 22, and 25 were inter-dune. Sampling sites numbered 2, 5, 8, 11, 14, 17, 20, 23, and 26 were dune slope, and the remaining nine sampling sites were dune crest (Fig. 2).

Field surveying and chemical analysis methods

Ten plots of 20 × 20 m from each sampling site were randomly selected at 200-m intervals, with 270 plots sampled in three types of terrain. For each plot, we recorded species, measured the crown width of each shrub and tree by “cross” methods [coverage was calculated using the formula of elliptical areas, $C = \pi XY/4$, where X and Y refer to the major and minor axis length of each respective crown (Phillips and MacMahon 1981)]. We selected three 1 × 1-m subplots of each plot along the diagonal and identified species, and visually estimated coverage of herbs (Causton 1988). Three soil samples from soil layers of 0–30 cm were taken from each plot. Wet and dry weights of all soil samples were used to calculate soil water content. We then mixed samples from one plot into one sample and measured the chemical properties of the soil. The weight of each mixed soil sample was approximately 1 kg. The pH was determined in a 1:2.5 (*w:v*) suspension of soil in water using a pH/ORP/°C meter (Hanna, Italy). Total salt content was determined using a EC/TDS/°C meter (Hanna, Italy). Organic matter content was determined by the Tyurin method. Total nitrogen (N) (%) was ascertained by the micro-Kjeldahl procedure after digestion with concentrated H₂SO₄ and measurement of NH₃ by the indophenol blue method using an autoanalyzer. Total potassium (K) (%) was ascertained by

Fig.1 Research area and sampling plots in the southern region of Gurbantüggüt Desert

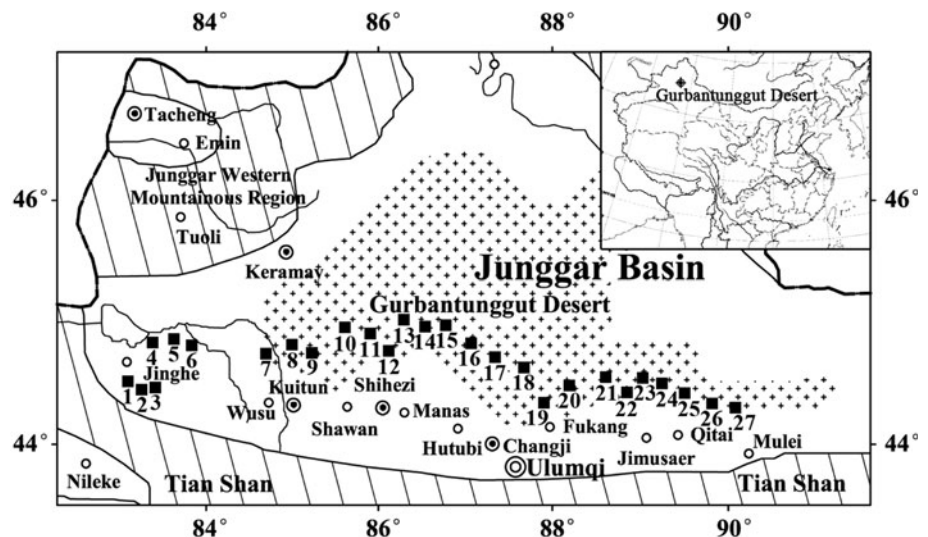
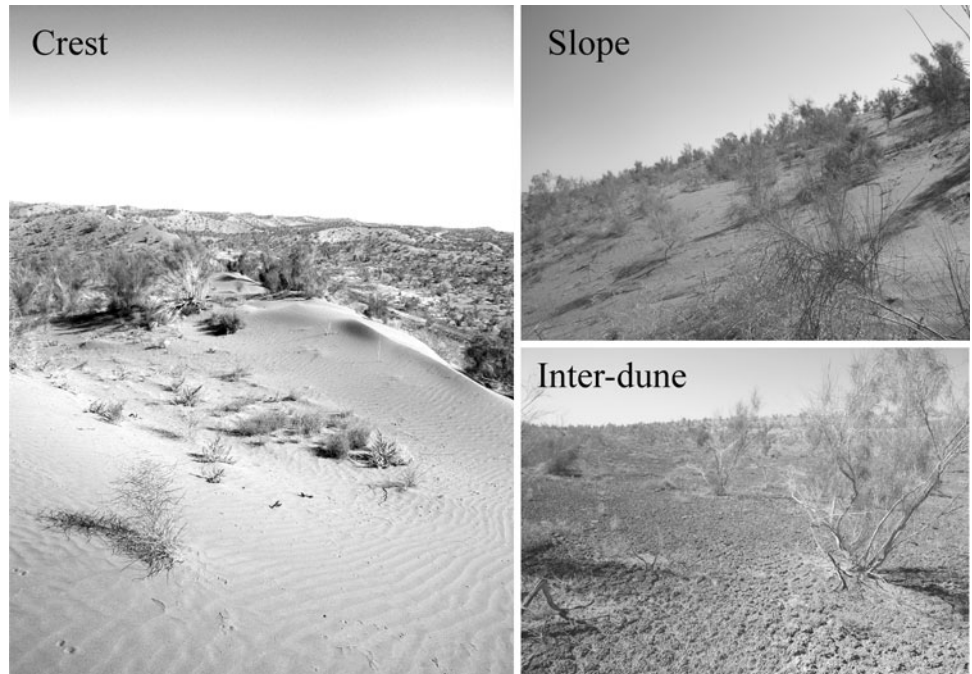


Fig. 2 Three terrains of sampling site in the southern Gurbantüנגgüt Desert



NaOH fused flaming spectrum method, and total phosphorus (P) (%) was determined using the $\text{HClO}_4\text{--H}_2\text{SO}_4$ method. The number of species in each square was used as the parameter of species richness (Sang 2009). Wind erosion was determined as described by Liao et al. (2008). Briefly, the aeolian sand transport was measured between May 1 and May 30, 2008, by using sandy samplers of $2 \times 2 \times 20$ -cm caliber to collect sand from each sampling site by the end of April. Sand was dried in an oven at 80°C for 24 h and weighed in a laboratory. The relative wind erosion was represented as the percentage of actual aeolian sand transport compared to the maximal aeolian sand transport in the sampling sites.

Redundancy analysis

We used Monte Carlo tests to select significant environmental variables ($p < 0.05$) in the sampling sites. The environmental factors that significantly influenced the vegetation coverage and species richness were soil water content, pH value, organic matter content, total salt content, evaporation, precipitation from April to June and terrain. Other environmental factors did not significantly influence vegetation coverage and species richness and thus were not included for RDA analysis (Table 1). A matrix of [environment \times sampling sites] $_{7 \times 27}$ was generated based on the Monte Carlo tests. Vegetation coverage was calculated and a matrix [coverage \times sampling sites] $_{10 \times 27}$ was generated. Vegetation species richness was calculated and a matrix [species richness \times sampling sites] $_{10 \times 27}$ was generated. Spatial location included longitude and latitude and a matrix of [spatial location \times sampling sites] $_{2 \times 27}$ was generated. These

matrixes were used to analyze the relationship between vegetation and environmental factors by CANOCO4.5 software (redundancy analysis, ter Braak and Šmilauer 2002).

Data analysis

Vegetation coverage and species richness were calculated for each of the ten sites. For the relationships between vegetation coverage, species richness, and wind erosion, we applied single regression and stepwise regression procedure to explore possible trends using SPSS, ver. 11.5 for Windows.

Results

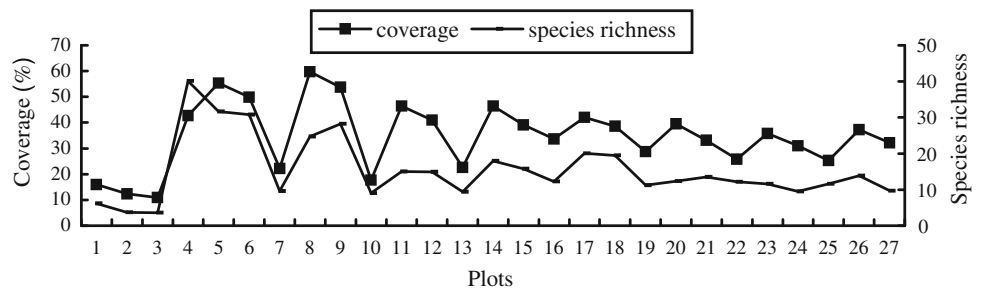
Characteristics of vegetation distribution

A total of 75 plant species were identified in the sampling sites of the southern Gurbantüנגgüt Desert. There were 9–40 species in the middle areas of Gurbantüנגgüt Desert, 10–20 species in the eastern areas, and less than six species in the western areas (Fig. 3). The distance from east to west was approximately 600 km. The plants develop well on slopes, which are preferable to crests because of the better comprehensive conditions. There are usually mobile dunes of 5–7 m width in most crests and vegetation is difficult to develop, but the vegetation in the residual crest develops well. In addition, the soil in most sampling sites was either saline–alkaline, which are relatively high (average total salt content up to 0.72 g/kg) or takyric solonets in inter-dune, which restrained most plants: as

Table 1 Forward selection analysis and Monte Carlo test of environment factors that impact community coverage and species richness

Environment factor	Coverage		Species richness	
	<i>p</i> value	<i>R</i> value	<i>p</i> value	<i>R</i> value
Soil water content (%)	0.002	0.13	0.002	0.32
pH value	0.020	0.04	0.020	0.02
Organic matter (g/kg)	0.042	0.02	0.020	0.01
Total salt content (g/kg)	0.001	0.28	0.002	0.25
Total nitrogen (g/kg)	–		–	
Total phosphorus (g/kg)	0.310		0.260	
Total potassium (g/kg)	0.090		0.210	
Evaporation (mm)	0.002	0.01	0.020	0.02
Annual precipitation (mm)	0.080		0.130	
Precipitation from April to June (mm)	0.001	0.34	0.002	0.17
Accumulated temperature (> 10°C) °C	–		–	
Average annual temperature (°C)	0.750		0.820	
Sun hours (h)	0.421		0.600	
Wind speed (m/s)	0.324		0.760	
Windy day (day)	0.274		0.610	
Terrain	0.002	0.06	0.020	0.12

$p < 0.01$ indicates the impact of environment factors on vegetation coverage and species richness is significant at the 0.01 level; $p < 0.05$ indicates the impact of environment factors on community types is significant at the 0.05 level. “–” indicates collinearity relationship exists between environment factors and other environment factors. *R* value represents relative percentage. Terrain is evaluated by artificial method: inter-dune 0, slope 0.5, crest 1

Fig. 3 Vegetation coverage and species-richness index in each plot of the southern Gurbantünggüt Desert

a result, the vegetation coverage and species richness of most crests is greater than in inter-dune areas. Therefore, the trend of average values of vegetation coverage and species richness was: slope > crest > inter-dune.

The species change with the terrain in the growth season. The main plants in dune crests were *Aristida Pennata* and *Agriophyllum squarrosum*, in the slopes shrubs or small semi-shrub such as *Calligonum leucocladium* and *Artemisia arenaria* were dominant, while in inter-dune areas, *Reaumuria soongorica* and *Ceratoides latens* were dominant. During May and June, ephemeral and ephemeroïd plants predominantly occupied the underlayer of vegetation communities. Vegetation coverage at each sampling site was mainly influenced by the distribution of ephemeral and ephemeroïd plants.

The relationship between the vegetation coverage, species richness, and environmental factors

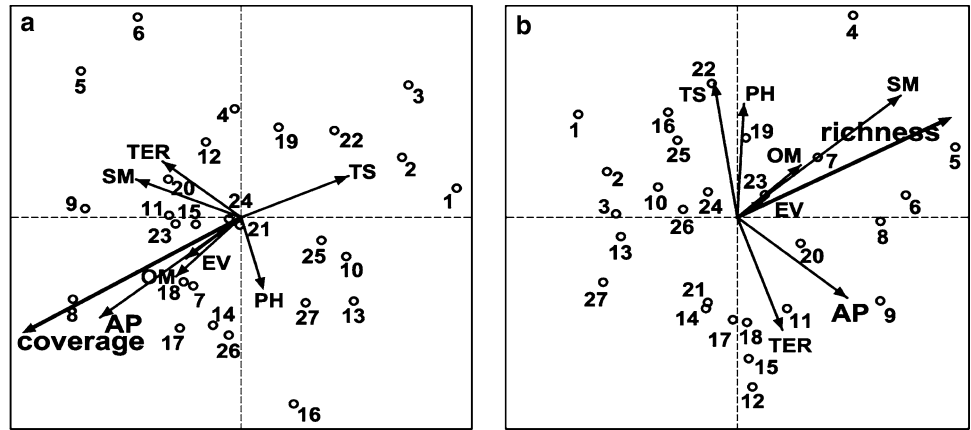
The principal factor that influenced vegetation coverage was precipitation from April to June, followed by soil salt content, soil water content, and terrain. Other

factors did not have a significant effect on vegetation coverage (Fig. 4a). The order of precipitation from April to June was that the largest quantity of rainfall was in the middle areas, then in eastern areas, and the smallest was in the western areas. A similar trend was observed for the vegetation coverage (middle areas > areas > western areas). Species richness was most significantly correlated with soil water content, followed by soil total salt content, precipitation from April to June, and terrain. Other factors had minor effects on species richness (Fig. 4b). As the soil water content decreased, the number of plant species decreased. The order of the soil water content was: sampling sites 4–6 > sampling sites 7–27 > sampling sites 1–3. A similar order was observed for species richness (sampling sites 4–6 > sampling sites 7–27 > sampling sites 1–3).

The relationship between the vegetation coverage, species richness, and the stability of dunes

Vegetation, terrain, and environmental factors influenced wind erosion. The order of relative wind erosion among the

Fig. 4 RDA analysis between vegetation coverage, species richness, and environmental factors



three terrains was: crest > slope > inter-dune. Relative wind erosion in inter-dunes was the lowest (mean value 5.38%, within 2.43–8.5%) in slopes it was medium (mean value 22.03%, within 3.03–100%), and in crests it was the highest (mean value 40.02%, within 4.00–93.93%). Thus, there were marked differences among the three terrains in relative wind erosion ($p < 0.01$, Fig. 5a–f). Using single regression procedure, it was determined that there were no significant correlations between vegetation coverage and wind erosion in inter-dune sites ($R^2 = 0.001$, $p > 0.05$). In slopes, the vegetation coverage was relatively large (>35%), and negatively correlated with wind erosion ($R^2 = 0.718$, $p < 0.01$). The strength of wind in crests was greater than that in inter-dunes and slopes, and the vegetation coverage in the crests is relatively low and negatively correlated with wind erosion ($R^2 = 0.753$, $p < 0.01$, Fig. 5a–c). The relationship between species richness and wind erosion is dependent on the terrain. In inter-dune sites, species richness was weakly correlated with wind erosion ($R^2 = 0.009$, $p > 0.05$), while in the slopes and crests, species richness was negatively correlated with wind erosion ($R^2 = 0.345$ and 0.682 , $p < 0.01$) (Fig. 5a–f). Wind strength in sampling sites 2 and 3 was relatively strong, with an average speed of 3.7 m/s. Wind erosion caused rough sands to be the main component of the soil in these areas. Strong evaporation and less precipitation maximally limited the development of ephemeral plants, leading to low vegetation coverage, less plant species, and great wind erosion.

The relationships between wind erosion and vegetation coverage and species richness were also explored using stepwise regression procedure in dune slopes and crests. The standard partial regression coefficient was -0.72 in vegetation coverage and -0.07 in species richness ($p < 0.01$ and $p = 0.32$, respectively). Results showed that relative wind erosion was mainly affected by vegetation coverage in both slopes and crests.

Discussion

The effect of environmental factors on vegetation coverage and species richness is relatively complex (Huntly

and Reichman 1994; Ojeda et al. 2000; Kerley et al. 2004). Zheng et al. (2006) showed that the vegetation coverage in Ordos Plateau was mainly affected by precipitation. Sang (2009) showed that, on a small scale, the vegetation coverage in the southern Gurbantünggüt Desert was mainly affected by soil water content. Qian et al. (2008) showed that on a large scale, species richness in the southern Gurbantünggüt Desert was probably caused by the shape of the dune. From the inter-dune to the dune crest, the coverage of trees, shrubs, and herbs was mainly affected by the saline-alkaline content in the soil. Our results show that vegetation coverage on different scales was influenced by different environmental factors. On a large scale, vegetation coverage was mainly influenced by precipitation from April to June, followed by soil salt content. Vegetation coverage decreases as precipitation decreases (Fig. 4a). Our results indicated that in the western area, precipitation from April to June was 29 mm and the average vegetation coverage was only 13% during this period. In the middle area, precipitation from April to June was 47–58 mm and the average vegetation coverage was up to 42%. The precipitation and vegetation coverage in the eastern area was medium. The reason for the relative high coverage is that ephemeral and ephemeroïd plants are “rainfed plants”, which avoid drought and complete their life history in a short time (Rooyen et al. 1992), and their coverage could reach 51.8% in May, so ephemeral and ephemeroïd plants are the main factors influencing vegetation coverage (Wang et al. 2003). Species richness was mainly determined by soil water content. Species richness increases as soil water content increases (Fig. 4b). In addition, precipitation from April to June also had an important influence on species richness. The number of species decreases as precipitation from April to June decreases. In this study, the precipitation in sampling sites 4–6 was not high (43 mm), but these sampling sites were close to Erbinur Lake and the underground water table was high, which resulted in the abundant species.

On a small scale, vegetation coverage was influenced by both soil water and salt content, and these effects were dependent on the terrain. In dune slopes and crests,

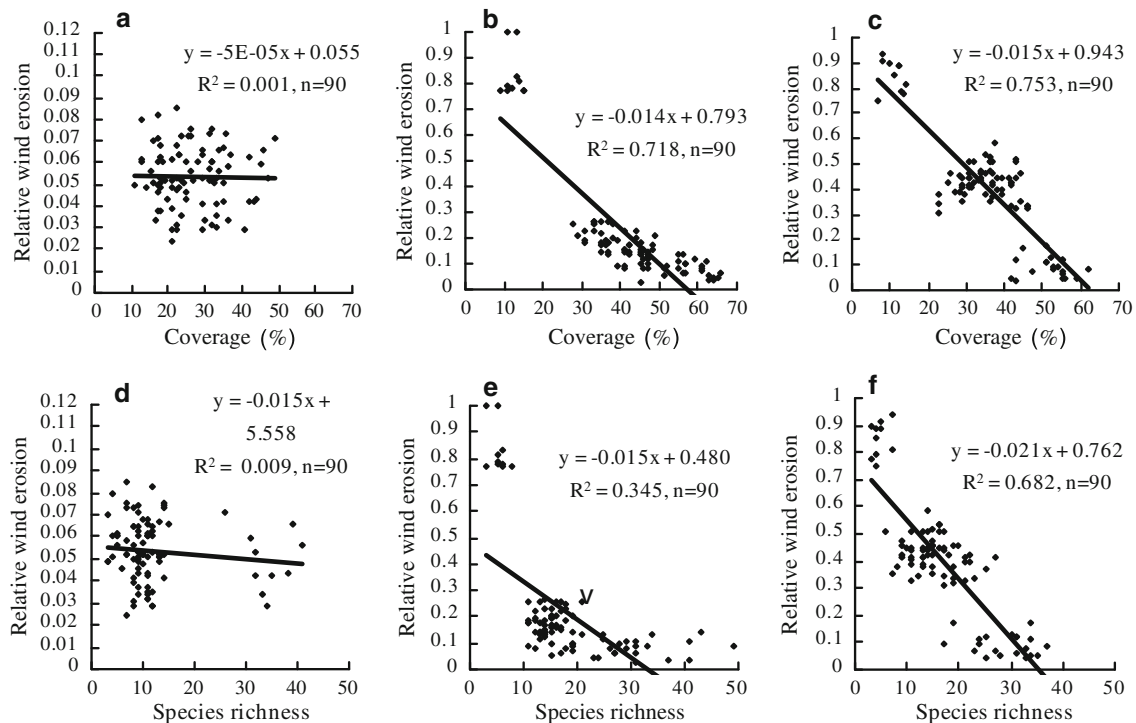


Fig. 5 Relationships between vegetation coverage, species richness, and relative wind erosion in different terrains. Each equation is calculated based on 90 data points by regressive method

soil water content was the main environmental factor affecting coverage. In arid environments, plants may be exposed to long-term drought conditions. Because of the huge deficit between precipitation and potential evapotranspiration, a reduced supply of water is the major threat to plants (Shan et al. 2008). Small-scale variation in vegetation, soil surface cover, and soil texture, alters the amount of water available to plants (Whitford 2003). Therefore, water is a dominant factor that restricts the development and growth of plants (Kimura et al. 2005; Shan et al. 2009). In inter-dune areas, soil salt content was the main factor affecting coverage. Perhaps soil salt content affects plant species dynamics through the variety of niches available and competition (Ungar 1974; Rozema 1996), and thus vegetation coverage decreased with increases of soil salt content (Fig. 4a).

Variation of environmental factors results in diversity of vegetation distribution. At the same time, the formation and development of vegetation influences the environment. In desert ecosystems, expanding vegetation coverage can increase the roughness of the aerodynamics, enhance the resistance of earth's surface on the airflow, relieve the erosion of the earth's surface, and reduce the rate of wind erosion, and so affect the stability of dunes. The effect of vegetation coverage on dune stability has been preliminarily elucidated, showing that with increases of vegetation coverage, the activity of the dune surface decreases (Wolf and Nickling 1993; Wang et al. 2003). Studies on the Kalahair and Gurbantünggüt Deserts found that when vegetation coverage exceeds 14%, the activity coefficient tends to be

stable (Wiggs et al. 1995; Wang et al. 2003). A wind tunnel experiment showed that when vegetation coverage reaches 35–40%, almost no wind erosion occurs (Wasson and Nanninga 1986).

We found that vegetation coverage and species richness in the southern Gurbantünggüt Desert were inconsistent with wind erosion in different terrains (Figs. 3, 5a–f). The relationship between vegetation coverage, species richness, and dune surface activity are dependent on the terrain. In dune slopes and crests, ephemeral and ephemeroïd plants developed very well in May, which can efficiently control the activity of dune surfaces (Wang et al. 2003). Thus, wind erosion was negatively correlated with vegetation coverage and species richness (Figs. 5b, c, e, f). Studies also showed that in inter-dune sites, soil biological crusts developed well, or hard salt crust is easily formed in the soil, which can efficiently reduce wind erosion. Therefore, wind erosion in inter-dune sites is weakly correlated with vegetation coverage and species richness.

The individual regression model indicated significant relationships between relative wind erosion, and vegetation coverage and species richness in slopes and crests (Fig. 5b, c, e, f). In this experiment, species richness changes with vegetation coverage in most of sampling sites ($R^2 = 0.647$, $p < 0.01$), the species richness was significantly related with wind erosion (Fig. 5e, f). However, the results of stepwise regression procedure indicated that wind erosion was not significantly affected by species richness. We deduced that species richness may have an impact on wind erosion through vegetation

coverage. This result agrees with the findings of Bressolier and Thoma (1979) and Wei et al. (2007).

Based on these findings, different methods of re-vegetation should be adopted for different terrains. In inter-dune areas, wind erosion is low. Salt-intolerant shrubs and herbs such as *Reaumuria soongorica* and *Ceratoides latens* should be appropriately developed and reduce the human disturbance. The dune slope is a major type of dune terrain. It is the key area to prevent the flow of sand on the crest and to maintain the stability of the inter-dune surface. Because of good water conditions in the soil, the dune slope has the ability to develop vegetation. Therefore, shrubs or small semi-shrub such as *Haloxylon ammodendron*, *Calligonum leucocladum*, and *Artemisia arenaria* can be planted in these areas. Soil water content in the crest is poor and wind erosion is strong. In addition to closer management, we need to choose drought and wind-resistant species such as *Aristida Pennata*, *Salsola collina*, and *Agriophyllum squarrosum*, making use of the suspended wet sand layer formed by snow melting and precipitation during spring, thus increasing the vegetation coverage and species richness.

Conclusions

We found that the environmental factors in the southern Gurbantünggüt Desert caused remarkable differences in vegetation coverage and species richness. On a large scale, the order of vegetation coverage and species richness was: sampling sites 4–6 > sampling sites 7–27 > sampling sites 1–3; that is, vegetation coverage decreased as precipitation decreased. On a small scale, the variation trend in average values of vegetation coverage and species richness was: slope > crest > inter-dune; that is, vegetation coverage increased as soil water content increased in slopes and crests, and as soil salt content decreased in inter-dunes; species richness decreased as soil water content decreased and soil salt content increased. Wind erosion has significant differences among the three terrains and the order was: crest > slope > inter-dune. In the inter-dunes, wind erosion was weakly correlated with vegetation coverage and species richness ($p > 0.05$). In the slopes and crests, wind erosion was significantly correlated with vegetation coverage and species richness ($p < 0.01$). The results of stepwise regression procedure indicated that wind erosion was not significantly affected by species richness. Wind erosion was mainly affected by vegetation coverage in both slopes and crests. The species richness may have an impact on wind erosion through vegetation coverage. Therefore, to reduce the advance of desertification, salt-intolerant shrubs and herbs should be appropriately developed in the dune slope; the inter-dune reduces interference. In crests, we need to choose drought- and wind-resistant species and provide closer management because the condition of soil water is poor and the wind is strong.

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