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ORIGINAL ARTICLE

Microbiotic crusts and their interrelations with environmental factors in the Gurbantonggut desert, western China

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Abstract Located in the Junggar Basin in Xinjiang, the Gurbantonggut Desert is the second largest desert in China. Microbiotic crusts consisting of animalcule, lichen, moss, and algae species develop extensively in the region. Their formation, species composition and distribution pattern are closely related to the environmental conditions along the different parts of sand dune. Analysis of microbiotic crust distribution and relationship to environmental factors shows that average microbiotic crust thickness is 0.05–0.1 cm at the tops dunes, 0.2–1.5 cm in the upper part, 1.5–2.5 cm in middle and lower parts of dunes, and 1.5–5.0 cm in interdune areas, while areal coverage is 30.5, 48.5, 55.5, and 75.5%, respectively. Microbiotic crust differentiation along dune slopes is a result of the development stage and converse-succession resistance of the different microbiotic crusts. The numbers of species, thickness and degree of development of microbiotic crusts increase from the upper part to the middle and lower parts of dune slopes. The development and differentiation of microbiotic crusts at various dune slope positions are a reflection of the ecological expression of the comprehensive adaptability and natural selection of different microbiotic crust species to the local environmental conditions, and are closely related to such ecological conditions as the physiochemical properties of soils and topsoil textural stability.

Keywords Microbiotic crust · Distribution · Environmental explanation · Gurbantonggut Desert · China

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Introduction

As organic complexes composed of various biotic components, including mosses, lichens, algae, and bacilli within topsoil, microbiotic crusts can exist in various desert habitats. Due to their peculiar physiological and ecological processes, they develop extensively in all arid and semiarid deserts in the world (West 1990; Belnap et al. 1994). In terms of environmental protection and ecological regeneration in arid areas, microbiotic crusts play a significant role in the occurrence, development and control of desertification, and have attracted growing attention as a theme for research. Research results reveal that microbiotic crusts in deserts can not only fix the position of sand dunes, reduce soil erosion by wind or water and effectively control the movement of mobile dunes, but also have such ecological functions as changing the physiochemical properties of soils and affecting surface hydrological processes and soil nutrient circulation in deserts (more detailed discussions can be found in Eldridge and Greene 1994; Belnap and Lange 2001; Belnap 2003). By increasing the content of soil organic matter, microbiotic crusts can provide the growth conditions for vascular plants, promote vegetation succession, affect ecosystem and landscape changes in deserts, and improve ecological quality (Belnap and Gardner 1993; Eldridge and Greene 1994; Li et al. 2000; Belap 2002).

As the second largest desert in China, the Gurbantonggut Desert is located in the Junggar Basin, which is typical of temperate deserts in the world (Fig. 1). Desert vegetation in the basin features psammophyte communities, as well as typical salt desert plant communities and a large number of ephemeral and ephemeral-like plants. Plentiful species of lichens, mosses and algae there have contributed to the formation of microbiotic crusts, 2–5 cm in thickness. In the southern part of the Gurbantonggut Desert, microbiotic crusts cover as much as 70–80% of the desert area. Except for spermatophytes, microbiotic crusts play an important biological role in fixing sand dune surfaces in the Gurbantonggut Desert and here has been growing research on microbiotic crusts in this region (Zhang et al. 2002). This paper seeks to reveal the characteristics of occurrence of microbiotic crusts and their environmental significance in relation to dune surfaces in the Gurbantonggut Desert. Analysis is made of the physiochemical properties of soils at different dune slope positions to illuminate the formative processes and distribution patterns of microbiotic crusts in the desert. Finally, the paper further examines the ecological functions and significance of microbiotic crusts in controlling sand movement and fixing dunes in arid deserts.

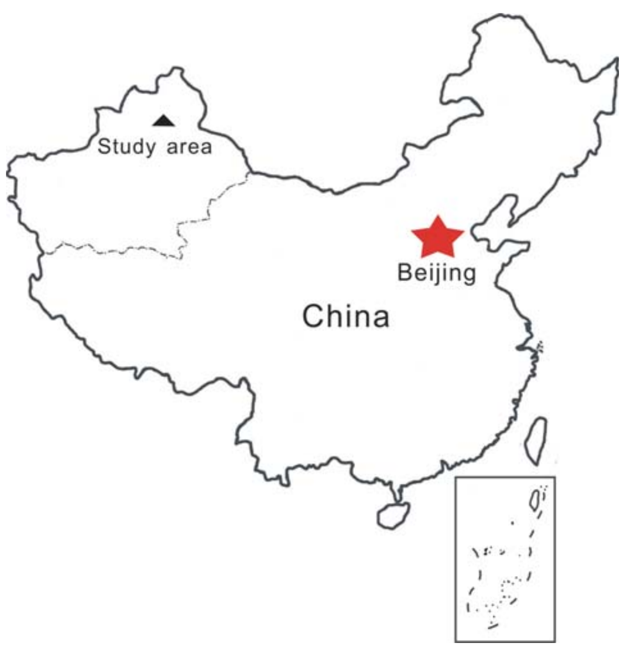

Fig. 1 Location of the Gurbantonggut Desert in western China

The study area and sampling

The study area

As the largest fixed and semi-fixed desert in China, the Gurbantonggut Desert is in a zone of 44°11′–46°20′N and 84°31′–90°00′E, covering an area of 4.88×10^4 km^2. Fixed and semi-fixed dunes occupy 87% of the total area of the desert. With a trend of roughly NW–SE and heights of 15–20 m, most dunes are fixed or semi-fixed in position. Vegetation covers 15–55% of the dune surface area as a whole, but exhibits variations between fixed dunes (40–55%) and semi-fixed dunes (15–25%). Average annual precipitation in the desert is less than 150 mm, with even less (70–100 mm) in the hinterlands of the desert. Precipitation mainly falls in spring; here is little precipitation in winter. In contrast, average annual evaporation is over 2,000 mm. Annual air temperature in the region varies in a range of 6–10°C, while maximum temperature is over 40°C. Total annual solar radiation varies from 5,692 to 6,360 MJ/m^2, with 2,780 to 2,980 cumulative sunlight hours. There are some psammophytes in the study area, including small semi-arbors, shrubs, and small semi-shrubs (Table 1). Ephemeral and ephemeral-like plants grow extensively and their average coverage can be as high as about 40% in May. Microbiotic crusts in the Gurbantonggut Desert feature many species, but the most extensively distributed and developed are animalcules, algae, lichens, and mosses. Except for spermatophyte, they form an important biological factor in fixing the position of sand dune surfaces in the region.

Table 1 Main species in the study area

	Species
Small semi-arbors	*Haloxylon ammodendron* and *Haloxylon persicum*
Shrubs small semi-shrubs	*Ephedra distachya*, *Calligonum leucocladum*, *Artemisia arenaria*, and *Seriphidium terrae-albae*
Ephemeral ephemeral-like plants	*Geraniaceae* sp., *Alyssum linifolium, Trigonella tenella, Carex physodes, Hypecoum parvifiorum, Eremurus anisopteris, Lappula rupestris*, and *Erysimum cheiranthoides*

Sampling and test of samples

The sampling plots selected are located in the southern part of the Gurbantonggut Desert where microbiotic crusts are best developed. In order to compare and analyze the characteristics of microbiotic crust occurrence at different positions on dune slopes, the species, coverage degree and thickness of microbiotic crusts, and the vegetation distribution pattern at the upper, middle, and lower parts of dune slopes and in interdune areas were surveyed. Moreover, soil crust samples and soil samples were also collected from the depths of 0 to 20 cm at the upper, middle, and lower parts of dune slopes to reveal the characteristics of microbiotic crust occurrence and differentiation over the different underlying desert surfaces in the Junggar Basin. The sand dunes are usually 18–20 m in height.

In accordance with international standard soil analysis procedures, different methods were used to measure the following physiochemical properties of the soil samples: soil granularity using the densimeter method; soil moisture contents using the drying method; soil organic matter content using the $K_2Cr_2O_7$ method (GB9834-88); total N using $CuSO_4$-Se powder diffusion method (GB7848-87); total P using the NaOH Melting-Mo Te Sc Colorimetry method (GB7852-87); total K using the NaOH Melting-Flaming luminosity method (GB7854-87); available P using the 0.5 mol/L $NaHCO_3$ Leaching-Mo Te Sc Colorimetry method; available N using the Alkali hydrolization-diffusion method; and available K using the 1 mol/L NH_40Ac Leaching-flaming luminosity. Soil pH-values were measured using PHS-2C digital acidimeter; soil conductance values using DDS-307 conductometer; total salt values using the weight method; CO_3^{2-} and HCO_3 in aqua-soluble salts in soil using double-indicator titer; Cl^- values using silver nitrate titer; SO_4^{2-}, Ca^{2+}, and Mg^{2+} values through EDTA capacity measurement; and K^+ and Na^+ values using flame photometry (Fig. 2).

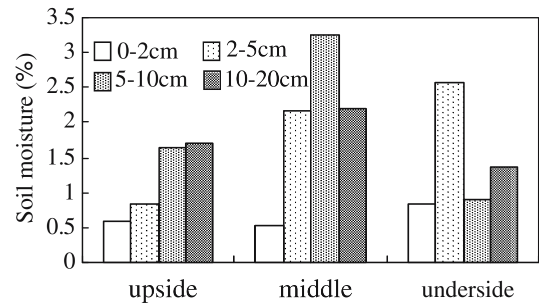

Fig. 2 Soil moisture content at different parts of a sand dune

Analysis

Physiochemical properties of crusted soils

Granular characteristics

Surface materials in the Gurbantonggut Desert are predominantly medium-sized sand and finer materials, which account for 78.74–94.56%. Medium-sized, fine, and extremely fine sands account for 73.01–82.62%, silt 5.15–14.15%, and clay with a grain size smaller than 0.005 mm and extremely coarse sand with a grain size bigger than 1.00 mm only 0.58–1.76 and 0.01–0.33%, respectively.

Soil grain composition affects the formation and development of microbiotic crusts in arid deserts. Material composition analysis reveals that in the Gurbantonggut Desert, the granular characteristics of soils vary with positions along landforms. The following patterns can be discerned (Table 2):

1. The proportion of materials finer than extremely fine sand (<0.25 mm) gradually increases from the upper part of dune slopes to the middle and lower parts and in the interdune areas; the percentages of extremely fine sand, silt, and clay increase from 9.69–13.23, 5.15–6.34, and 0.58–0.81%, at the upper part of dune slopes to 28.96–29.49, 13.79–14.15, and

Table 2 Soil particle size distribution on a sand dune surface

Position in sand dune	Depth (cm)	Clay <0.005	Silt 0.063–0.005	Extremely fine sand 0.125–0.063	Fine sand 0.25–0.125	Medium sand 0.5–0.25	Coarse sand 1–0.5 mm	Extremel coarse sand 1–2 mm
Upper part	0–2	0.81	6.34	13.23	27.01	34.43	17.85	0.33
	2–5	0.58	5.15	9.69	23.17	40.15	21.14	0.12
Middle part	0–2	1.33	11.29	26.38	31.08	23.29	6.61	0.02
	2–5	1.21	10.48	26.45	30.48	25.69	5.68	0.01
Lower part	0–2	1.76	14.15	29.49	27.72	20.65	6.21	0.02
	2–5	1.63	13.79	28.96	26.95	23.23	5.44	

1.63–1.76%, at the lower part of dune slopes and the interdune areas, respectively. There is a gradual drop in the percentage of medium-sized sand and coarse sand along is same trend.
2. There is good sand sorting in the upper part of dune slopes and medium-sized sand dominates the surface material composition there (34.43–40.15%), followed by fine sand (23.17–27.01%), and coarse sand (17.85–21.24%); Content of silt and clay is the least (less than 10%). At the middle part of dune slopes, fine sand is dominant (30.48–31.08%), followed by extremely fine sand and medium-sized sand. There is a sharp drop in the content of coarse sand (only at 5.68–6.61%), a notable increase in silt content (over 10%), in the middle dune parts. At the lower part of dune slopes and in the interdune areas, extremely fine sand is dominant, followed by fine sand and medium sand. There is a notable rise in the silt and clay content (over 15%).
3. A comparison of soil composition at different soil depths reveals that except for extremely fine sand at the middle part of dune slopes, the total proportion of materials finer than fine sand at the depth of 0–2 cm is higher than at the depth of 2–5 cm. In contrast, the proportion of medium-sized sand at the depth of 2–5 cm is higher than at the depth of 0–2 cm.

Soil composition directly affects soil porosity, soil bulk density, soil moisture contents, soil osmosis, soil cohesion, and so on. Generally, the poorer the sorting of deposits and the finer the soil grains, the weaker soil osmosis will be (Zhu and Ding 1991). There is poor deposit sorting at the lower part of dune slopes and in the interdune areas where the content of silt and clay increases significantly. Clay directly affects the formation and development of microbiotic crusts in that crusts increase in abundance and diversity as the proportion of clay rises. Fine materials reduce soil porosity and thus facilitate the formation of barriers to effective osmosis, hading to favorable conditions for the formation and development of microbiotic crusts and the growth of plants with shallow roots (Anderson and Calvin 1983).

Moisture contents of crusted soils

Variations in aeolian soil moisture content in arid deserts are extremely complicated and related to many factors (Zhang et al. 1999). In the Gurbantonggut Desert, seasonal changes in topsoil moisture content are mainly affected by rainfall and snowmelt water. Moreover, condensate water in sandy areas plays a role in soil moisture content changes and the growth of plants. Affected by climatic conditions, there are significant seasonal changes in the topsoil moisture contents in the region. Soil moisture content is high in spring and changes significantly when snow-cover begins to melt and more rain falls. In summer, soil moisture content drops but remains in a steady state as temperature increases, rainfall decrease, and moisture consumption by plant increases (Zhao et al. 2003). To examine the effect of microbiotic crusts on soil moisture and composition, soil moisture content at depths of 0–2, 2–5, 5–10, and 10–20 cm were measured at different positions on dune slopes in the survey. The results show that soil moisture content is obviously different at different dune slope positions and different depths. Soil moisture content increases with depth within 20 cm of the surface along the upper part of dune slopes. The highest soil moisture content occurs at the depth of 10–20 cm. There is a pattern in the change of soil moisture content, with highest soil moisture content occurring at depths of 5–10 cm along the middle and lower parts of dune slopes, and the lowest content at depths of 0–2 cm. Soil moisture content at depths of 0–2 cm increases to some extent along the lower part of dune slopes and in the interdune areas. These values are similar to those at depths of 5–10 cm. The highest soil moisture content occurs at depths of 2–5 cm. This is obviously different from the situation along the upper part of dune slopes, where soil moisture content increases with depth. Microbiotic crusts have a very significant effect on the infiltration of the limited rainfall and the movement of soil moisture. However, the mechanisms by which microbiotic crusts affect soil moisture transport are not yet fully understood. There are different views to explain the mechanisms of microbiotic crusts on rainwater infiltration. Many ephemeral plants grow and abundant microbiotic crusts are distributed along the lower parts of dune slopes and in the interdune areas in the Gurbantonggut Desert. There is a need to conduct further research on their effects on soil moisture content at different soil depths.

Salt content of crusted soils

The content of soluble salts in top soils of the Gurbantonggut Desert is slightly lower than that in other sand deserts. It varies between 0.020 and 0.032%. Analysis of soil salt content at depths of 0–5 and 5–15 cm along different dune slope positions reveals that soil salt content increases from the upper part to the lower part of dune slopes (Fig. 3). On upper parts of dune slopes, the

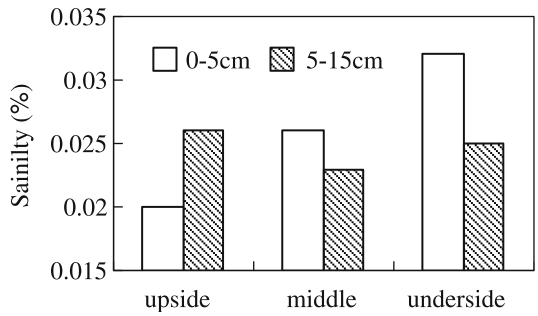

Fig. 3 Salinity levels at depths in a sand

content of soluble salts at depths of 0–5 cm from the top soil is low, with an average value of 78.95% in the study area. However, soil salt content at depths of 0–5 cm is higher than that at depths of 5–15 cm on middle parts of dune slopes and in the interdune areas. Salt content at depths of 0–5 cm is highest in the interdune areas. Total anion and total cation contents follow a similar pattern of variation (Table 3). The high contents of total salt, total anion and total cation in the topsoil in the interdune areas are possibly related to the aeolian action. It may also be related to the hydrological processes in the interdune areas.

The analysis results reveal that there are only very minor changes in exchangeable electropositive K^+, Ca^{++}, Mg^{++}, and Na^+ contents in the soils. However, it should be pointed out that the contents of Ca^{++} and K^+ are significantly higher than that of Mg^{++} and Na^+. The content of Mg^{++} is the lowest among them. This is likely to be related to the high content of K^+. The study reveals that an increase in K^+ content can reduce the content of Mg^{++} (Hunt et al. 1979). Exchangeable cations have a different effect on the soil colloid solution and can affect the growth of different microbiotic crusts, especially algal crusts. There is a positive correlation between the two.

pH-values and conductance of soil

Soil pH-value has an effect on different microbiotic crusts (Metting 1981). The analysis results show that the soils in the Gurbantonggut Desert are alkalescence, pH-values varying between 8.43 and 8.66. On upper and middle parts of dune slopes, the value at depths of 5–15 cm is slightly higher than that at 0–5 cm, whereas on lower parts of dune slopes and in the interdune areas, the soil pH-value at a depth of 0–5 cm is higher than that at 5–15 cm (Fig. 4). The soil pH-value on lower parts of dune slopes and in the interdune areas is slightly higher than that along upper and middle parts of the dune slopes. However, the difference is not great, revealing that soil eluviation is very limited. Moreover, pH-value analysis shows that the microbiotic crusts in the Gurbantonggut Desert are alkaline. Such an alalkalesence process is most notable on lower parts of dune slopes and in the interdune areas. Soil conductance in the region varies in a range of 0.051–0.074 ms/cm. It is high along lower parts of dune slopes and in the interdune areas. Soil conductance at depths of 0–5 cm from the topsoil is higher than that depths of 5–15 cm. Its pattern of change is similar to that of salt content and pH-value.

Nutrient change in soil crusts

Organic matter content in the soils of the Gurbantonggut Desert is low and varies in a range of 0.078–0.158%, reflecting low-organic matter accumulation (Table 4). Analysis shows that the organic matter content at depths of 0–5 cm from the topsoil is higher than that at depths of 5–15 cm in the upper, middle,

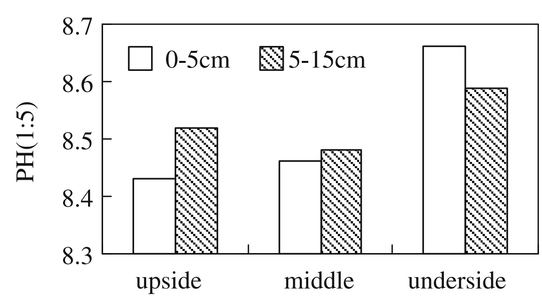

Fig. 4 PH-values at different soil in a sand

Table 3 Salinity levels at different soil depths on a sand dune surface

Position in sand dune	Depth (cm)	Salt content (%)	Anion (%)				Cation (%)			
			$CO_3^{=}$	$HCO_3^{=}$	Cl^-	$SO_4^{=}$	Ca^{++}	Mg^{++}	K^+	Na^+
Upper part	0–5	0.02	0	0.011	0.002	0.001	0.002	0	0.004	0
	5–15	0.026	0.001	0.011	0.003	0.003	0.002	0.001	0.004	0.001
Middle part	0–5	0.026	0	0.011	0.002	0.005	0.0045	0	0.003	0.0005
	5–15	0.023	0.001	0.0095	0.003	0.002	0.003	0.001	0.003	0.0005
Lower part	0–5	0.032	0	0.015	0.003	0.004	0.005	0.001	0.003	0.001
	5–15	0.025	0.001	0.014	0.001	0.001	0.004	0.001	0.002	0.001

Table 4 Nutrient contents at different soil depths on a sand dune surface

Position in sand dune	Depth (cm)	Organic matter (%)	Total (%)			Available (mg/kg)		
			N	P	K	N	P	K
Upper part	0–5	0.112	0.009	0.029	1.445	13.38	6.61	169
	5–15	0.085	0.008	0.026	1.517	32.92	5.43	167
Middle part	0–5	0.123	0.009	0.027	1.504	31.465	6.105	124
	5–15	0.078	0.008	0.026	1.408	29.875	3.995	125.5
Lower part	0–5	0.158	0.013	0.034	1.573	38.93	6.11	135
	5–15	0.082	0.008	0.028	1.571	20.72	2.39	92

and lower parts of dune slopes and in the interdune areas. Moreover, soil organic matter content increases from the upper part of dune slopes to the middle and lower parts and the interdune areas, with the peak value (up to 0.158%) occurring at depths of 0–5 cm along lower parts of dune slopes and the interdune areas (Fig. 5). Comparison reveals that the contents of N, P, and K in the soils change significantly at different dune slope positions. At depths of 0–5 cm from the topsoil, total N, total P, total K, and available N are all high, but available P and available K are low at depths of 5–15 cm. Nutrient changes in desert soil crusts are related to the geographical environment and the ecological activity of animalcules in the soils at different dune slope positions. In arid deserts, wind erosion is serious on dune slopes and the topsoil matrix is in continuous change. These affect the efficiency of soil animalcules' activities and soil nutrient accumulation. As a result, wind erosion is weak on the lower parts of dune slopes and in the interdune areas. However, aeolian deposition is active there, leading to relative stability of the topsoil matrix. Spring snowmelt and summer rainfall in the interdune areas promote the decomposition of aeolian deposits and the activity of animalcules. Moreover, microbiotic crusts are connected by hyphas and netted lichen. This improves both soil granular structure and the soil nutrient situation (Bailey et al. 1973).

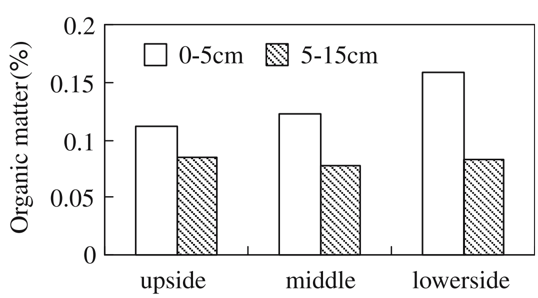

Fig. 5 Organic matter content at different soil depths in a sand dune in the Gurbantonggut Desrt

Interrelations with environmental factors

Distribution of microbiotic crusts

There are many biological species in the microbiotic crusts of the Gurbantonggut Desert. Those most extensively distributed and developed are animalcules, algae, lichens, and mosses. In the animalcule communities, bacilli, actinomyces, and epiphytes are dominant. The algal crusts in the region mainly include *Microcoleus paludosus, Microcoleus vaginatus*, and *Xenococcus lyngbyge*, among others, while the lichen crusts mainly include *Collema tenax, Psora decipiens, Xanthoparmelia desertorum*, and *Diploschistes muscorum*. The crusts dominated by mosses mainly include *Tortula desertorum, Crassidium chloronotos, Bryum argenteum, Tortula muralis*, and so on (Table 5). The development, succession, and pattern of microbiotic crusts are different between the upper, middle, and lower parts of dune slopes and the interdune areas. This is due to the different environmental conditions at varying dune slope positions in the Gurbantonggut Desert.

The areal differentiation of microbiotic crusts at different dune slope positions is related to their development stage and converse-succession resistance. In the Gurbantonggut Desert, different species in microbiotic crusts are distributed at varying dune positions. The animalcule community is an important component and represents vanguard species of microbiotic crusts. It exists in microbiotic crusts and is extensively distributed at all dune slope positions and in the interdune areas. At the top of drifting and semi-drifting dunes, it is the main species in microbiotic crusts. This shows that animalcule species have a strong adaptability to the topsoil matrix of dunes. Algal crusts are distributed on the upper and middle parts of dune slopes and in the interdune areas. Fully developed gray and offwhite algal crusts are distributed at the middle part of dune slopes. Although not very thick, these crusts possess a resistance to wind erosion. Lichen crusts are distributed at positions lower than that of

Table 5 Species and distribution of microbiotic crusts in the Gurbantonggut Desert

Species in microbiotic crust		Distribution and characteristics
Animalcule communities	Bacilli, actinomyces, and epiphytes	The top of mobile and semi-mobile dunes
Alga crusts	*Microcoleus paludosus*, *Microcoleus vaginatus*, *Xenococcus lyngbyge*, *Anabaena azotica*, *Lyngbya martensiana*, and *Chroococcus turgidus* var. *solitarius*	The upper and middle parts of dune slopes Thickness: 0.18–0.25 cm in upper parts and 0.25–0.50 cm in middle parts Color: gray and offwhite
Lichen crusts	*Collema tenax, Psora decipiens, Xanthoparmelia desertorum*, and *Diploschistes muscorum*	The middle and lower parts of dune slopes and the interdune lowlands Thickness: 0.18–0.25 cm in middle parts and 0.25–0.50 cm in lower parts Color: dark gray, brown or yellow
Moss crusts	*Tortula desertorum*, *Crassidium chloronotos*, *Bryum argenteum*, and *Tortula muralis*	The lower parts of dune slopes and the interdune lowlands Thickness: 0.6–1.2 cm in lower parts and 1.5–3.5 cm in the interdune lowlands Color: black, brown or light brown

algal crusts. Lichen crusts require both epiphytes and algae. As the number of epiphytes and algae is small at the top of dunes, lichen crusts are rare at the top and along the upper part of dune slopes. They are mainly distributed on the middle and lower parts of dune slopes and in the interdune areas. Dark gray, brown or yellow in color, these crusts develop in large areas, and are distributed extensively, forming the main microbiotic crust type in the Gurbantonggut Desert. Moss crusts are mainly distributed on the middle and lower parts of dune slopes and in the interdune areas and are black, brown or light brown in color. In these crusts, *Grimmia anodon* and *Grimmia pulvinata* are mainly found on the middle and lower parts of dune slopes, while *B. argenteum* and *Bryum capillare* are mainly distributed in the interdune areas. The topography of the interdune areas is gentle, making it easy for spring snowmelt water and summer rainwater to seep out, thus providing the environmental conditions for microbiotic crusts to develop. This is particularly favorable for the sexual reproduction and growth of mosses. As a result, microbiotic crusts are highly developed in the interdune areas in the Gurbantonggut Desert (Fig. 6).

Microbiotic crusts and topsoil matrix stability

Topsoil stability and local climate affect the formation and development of microbiotic crusts. Analysis of the stability of topsoil matrices where microbiotic crusts are developed reveals that topsoil matrix stability varies with dune slope position and significantly increases from the dune top to the lower part of dune slopes. This is mainly due to the frequent occurrence and high intensity of wind erosion or aeolian deposition along the dune tops and the upper parts of dune slopes. Field investigations and wind-tunnel experiments show that wind speed increases from the lower and middle parts of windward dune slopes to the dune top and reaches its peak value at the dune top (Li and Guan 1996; Hasi et al. 1999). Increased wind speed means greater sand transport capacity and enhanced surface activity intensity along the upper part of windward dune slopes and the dune top, thus reduced topsoil matrix stability. Observations from individual dunes in the Gurbantonggut Desert suggest that the transported sand quantity while wind seed exceeds 6 ms^{-1} from April to June increases from 1.10 g at the lower part to 5.26, 68.96, and 1,982.75 g at the middle and upper parts of windward dune slopes and the dune top, respectively, and that the transported sand quantity at the dune top is 2,000 times that of the interdune areas. Drifting sand is mainly distributed on the upper part of dune slopes and dune tops. The average wind erosion depth is 5.8 cm part of dune slopes and 8.65–19.00 cm at the dune top (Wang et al. 2003). The

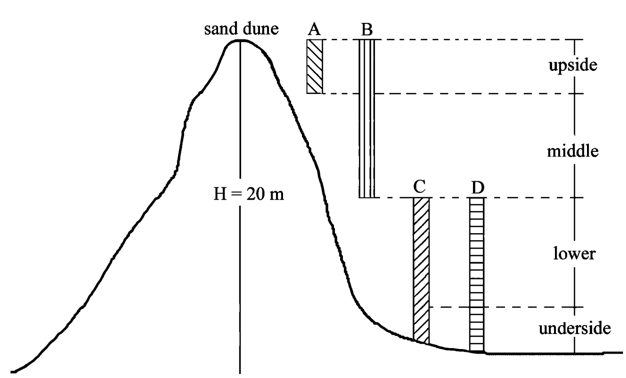

Fig. 6 Typical distribution pattern of microbiotic crusts along a sand dune in the Gurbantonggut Desert

topsoil matrices part of dune slopes and in the interdune areas is relatively stable. As for development and distribution of microbiotic crusts at different dune slope positions, average crust thickness is 0.05–0.1 cm dune top, 0.2–1.5 cm upper part, 1.5–2.5 cm middle, and lower parts of dune slopes and 1.5–5.0 cm in the interdune areas. Areal coverage is 30.5, 48.5, 55.5, and 75.5%, respectively. These reveal that the degree of development and quantity of microbiotic crusts increase from the dune top down to the lower part of dune slopes and the interdune areas. Furthermore, algal crusts are distributed at the upper part of dune slopes where wind erosion is intensified and the stability of sand surface matrix is poor. It can be concluded that algae-dominated microbiotic crusts have a strong converse-succession resistance and adaptability to changes in dune surface matrix stability (Fig. 7).

Changes in microbiotic crusts and plant communities

Analysis of vegetation in regions where microbiotic crusts are distributed shows that composition and structure of plant communities and vegetation coverage are different at different dune positions in the Gurbantonggut Desert. On the drifting sand surface at the dune top, plant communities are dominated by *Aristida adscensionis*, accompanied by *Corispermum elongatum, Horaninowia ulician*, *Olgaea leucophylla, Agriophyllum squarrosum*, *Erysimum cheiranthoides*, etc. However, vegetation coverage is low and varies in the range of 7.5–13.5%. Herbs, such as *Aristida Pennata*, that need long-term nutrients cover less than 7% of the area. The areal coverage of ephemeral plants varies between 1.5 and 4.5%. There are few microbiotic crusts distributed at dune tops and animalcules are dominant. At the middle and upper parts of dune slopes, the plant communities include *Haloxylon persicum, Calligonum leucocladum, Artemisia arenaria,*

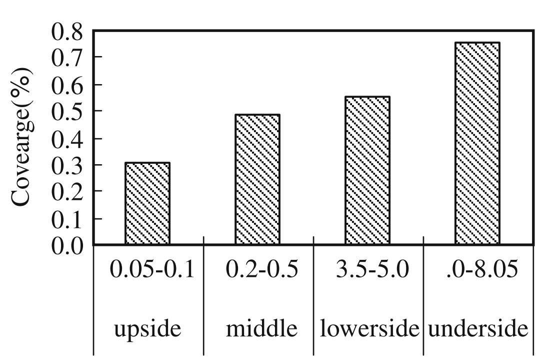

Fig. 7 The relationship between microbiotic crust thickness and coverage degree

Seriphidium terrae-albae, etc. Vegetation coverage varies between 15.5 and 28.5%. Other plants include *H. ulician*, *Soranthus meyeri*, *Ceratocarpus arnarius, Nonea Caspica*, *Chrozophora sabulosa*, *Carex physodes, Trigonella tenella, Hypecoum parvifiorum, Eremurus anisopteris, Lappula rupestris*, and others. Some well-developed algal crusts are distributed here and lichen crusts also occur. On the middle and lower parts of dune slopes and in the interdune areas, the plant communities are quite different from those at the upper part of dune slopes. They are dominated by *Ephedra distachya* and accompanied by *Geraniaceae* sp., *Alyssum linifolium, C. physodes, Bromus orientalis L.*, and *L. rupestris*. Vegetative cover is high, normally over 35% on the lower parts of dune slopes and in the interdune areas. The lichen *P. decipiens*, *X. desertorum*, and *D. muscorum* are most abundant. The mosses *B. argenteum* and *B. capillare* are distributed around the short shrubbery of *E. distachya* in the interdune areas. Plants in the sampling plots grow densely. However, the relationship between changes in plant community structure and the formation and development of microbiotic crusts at the different dune slope positions is not yet fully understood. More research needs to be conducted on the effect of extensively distributed mosses and lichens in the interdune areas on the development and succession of the *E. distachya* community in the formation of microbiotic crusts.

Conclusions and discussion

1. Medium-sized sand and finer materials are dominant in surface material composition of the Gurbantonggut Desert. For individual dunes, the content of fine material (<0.25 mm) increases from the upper part to the middle and lower parts of dune slopes and in interdune areas, but there is a decrease in the content of medium-sized sand and coarse sand. On the upper part of dune slopes, medium-sized sand is dominant average: 37.44%. On the middle part of dune slopes, medium-sized sand, fine sand, and extremely fine sand are dominant, while fine sand and extremely fine sand are dominant on the lower parts of dune slopes and in the interdune areas. Soil moisture content is high in spring, it drops notably summer. For individual dunes, soil moisture content is significantly different at ranging dune positions and depths. On the upper part of dune slopes, the highest soil moisture content occurs at depths of 10–20 cm. Among the middle and lower parts of dune slopes, the peak value occurs at 5–10 and 2–5 cm, respectively. In

the Gurbantonggut Desert, the content of soluble salts in soil is low. It is the lowest on the upper parts of dune slopes and increases significantly from the middle part of dune slopes to the lower part and the interdune areas. Soil organic matter content increases notably from the middle part of dune slopes to the lower part and the interdune areas, with the highest value occurring at depths of 0–5 cm. This is related to environmental conditions and the activity of animalcules in the formation of microbiotic crusts. Humus soil continuously forms on dune surfaces under the effect of mosses and lichens. This effectively promotes the accumulation of organic matter in poor soils and increases soil nutrients.

2. In the Gurbantonggut Desert, topsoil matrix stability varies at different sand dune positions. Wind erosion on sand surfaces increases gradually but the stability of the topsoil matrix falls from the lower part of windward dune slopes to the middle and upper parts and the dune top. The surface is extremely unstable at tops of dunes. The formation and development of microbiotic crusts are strongly affected by changes in topsoil matrix stability, local climate and soil physiochemical properties. For individual dunes, the distribution and kinds of microbiotic crusts are different between the lower, middle, and upper parts of dune slopes and the dune top. Animalcule crusts are mainly distributed at the drifting and semi-drifting sand surfaces along the dune top, algal crusts mainly at the upper and middle parts of dune slopes and lichen crusts extensively along the middle and lower parts of dune slopes and in the interdune areas, while moss crusts occur mainly at the middle and lower parts of dune slopes and the interdune areas. The development and differentiation of microbiotic crusts at different dune slope positions are a result of the ecological expression of the comprehensive adaptability and natural selection of different microbiotic crust species to the local environmental conditions, and are closely related to ecological conditions.

3. The formation and existence of microbiotic crusts make the physiochemical properties and biological properties of topsoil in sandlands significantly different from those of loose sandy soils. Microbiotic crusts as the vanguard species in the succession of plant communities are able to grow in the regions where soil is poor and vascular plants cannot thrive. During the formative process of microbiotic crusts, algae begin to grow around the roots of psammophytes and form alga-root crusts at first, followed by lichens (West 1990). Mosses begin to grow after algae and lichens have improved the local soil structure and soil moisture capacity. Humus soil forms continuously on the dune surface under the effect of mosses and lichens, which promote the accumulation of organic matter in poor soils and the enrichment of soil nutrients. The development and succession of microbiotic crusts play an important role in improving soil structure. It helps the stabilization of dune surfaces and the formation of fixed dunes and also provides the conditions for herbs and woody plants to grow (Hunt et al. 1979; Smith 1983).

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References

Anderson RW, Calvin A (1983) The influence of lichens on slope processes in some Spanish badlands. In: Thornes JB (ed) Vegetation and erosion. Wiley, London, pp 385–389

Belnap J, Harper T, Warren SD (1994) Surface disturbance of cryptobiotic soil crusts: nitrogenase activity, chlorophyll content and chlorophyll degradation. Arid Soil Res Rehabil 8:1–8

Belnap J, Gardner JS (1993) Soil microstructure in soils of the Colorado Plateau: the role of the cyanobacterium *Microcoleus vaginatus*. Great Basin Nat 53:40–47

Belnap J (2002) Nitrogen fixation in biological soil crusts from southeast Utah, USA. Biol Fertil Soils 35:128

Belnap J (2003) The world at your feet: desert biological soil crusts. Front Env 1:181

Belnap J, Lange OL (2001) Biological soil crusts: characteristics and distribution. In: Belnap J, Lange OL (eds) Biological soil crusts: structure, function, and management. Springer, Berlin Heidelberg New York

Bailey D, Mazurak PA, Rosowski JR (1973) Aggregation of soil particles by algae, J Phycol 9:9–101

Eldridge DJ, Greene RSB (1994) Microbiotic soil crusts: a view of their roles in soil and ecological processes in the rangelands of Australia. Aust J Soil Res 32:389–415

Hasi, Dong GR, Wang GY (1999) Near-surface airflow and slop morphology of dunes in southeastern Tengger Desert. J Desert Res 19(1):1–5

Hunt ME, Floyd GL, Stout BB (1979) Soil algae in field and forest environments. Ecology 60(2):362–375

Li XR, Zhang JG, Wang XP (2000) Study on soil microbiotic crust and its influences on sand-fixing vegetation in arid desert region. Acta Bot Sin 42(9):965–970

Li ZZ, Guan YZ (1996) Experimental study on imitative flow pattern of longitudinal dunes and transverse dunes. J Desert Res 16(4):360–363

Metting B (1981) The systematic and ecology of soil algae. Bot Rev 47:295–312

Smith EP (1983) Niche breadth, resource availability, and inference. Ecology 63:1675–1681

Wang XQ, Li BW, Zhang YM (2003) Stabilization of dune surface and formation of mobile belt at the top of longitudinal dunes in Gurbantonggut Desert, Xinjiang, China. J Desert Res 23(2):126–131

West NE (1990) Structure and function of microphytic soil crusts in wildland ecosystems of arid to semi-arid regions. Adv Ecol Res 20:179–223

Zhang YM, Cao T, Pan BR (2002) A study on bryophyte associated with formation of soil crust in South Fringe of Gurbantunggut Desert in Xinjiang, China. Acta Bot Boreal-Occident Sin 22(1):18–23

Zhang GS, Wang LH, Dong ZH (1999) The mechanical composition and seasonal water content of aeolian sandy soil in Mu Us Sandy Area. J Desert Res 19(2):151–155

Zhu CY, Ding TD (1991) Physics of drifting sand. Chinese Forestry Press, Beijing, pp 44–51

Zhao CJ, Lei JQ, Wang XQ (2003) The spatial distribution of the spring moisture in the hinter land of Gurbantonggut Desert. Arid Land Geogr 26(2):154–158