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The spatial distribution patterns of biological soil crusts in the Gurbantunggut Desert, Northern Xinjiang, China

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Abstract

The Gurbantunggut Desert, the largest fixed and semi-fixed desert in China, is characterized by a predominant coverage of lichen-dominated biological soil crusts, which serve an indispensable role in sand fixation. Two findings of biological soil crusts have been disclosed from previous field observations: first, distribution of biological soil crusts is selective upon locations; second, species composition varies significantly for the biological soil crusts that are at different developing stages. In this study, a strategy was developed to investigate the spatial distribution of biological soil crusts by coupling remote sensing data and field measurements. A crust index for the Landsat ETM+ data has been developed and applied to detect the lichen-dominated biological soil crusts in the Gurbantunggut Desert. The results indicated the South of the desert encompassed the most abundant biological soil crusts. Besides, biological soil crusts were distributed in uniform density in the South of the desert whereas their distribution patterns become patchier in the rest of the desert. Finally, statistics from the classification revealed that biological soil crusts covered 28.7% of the land in the whole study area. However, it is worth mentioning that the crusts coverage may be underestimated given the fact that detection of crusts from the Landsat ETM+ imagery is viable only if crusts constitute more than 33% of the instantaneous field of view (IFOV) of the Landsat ETM+ sensor.

Keywords: Lichen-dominated soil crusts; Remote sensing; Spectral features; BSCI index

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1. Introduction

Biological soil crusts, given their extraordinary abilities to survive desiccation and extreme temperatures (up to 70 °C), high pH, and high salinity, have been found in desert areas all over the world and may constitute as high as 70% of the living covers in some plant communities (Friedmann and Galun, 1974; West, 1990). Biological soil crusts play a vital role in ensuring proper structuring and functioning of desert ecosystems, such as engagement in the process of formation, stability and fertility of soil, prevention of soil erosion caused by wind or water, augment of vascular plant colonization, and stabilization of sand dunes (Belnap, 2003; Belnap and Eldridge, 2001; Eldridge and Greene, 1994). Recently, the issue of crust recovery from various kinds of disturbances such as global warming and intensified human activities has been addressed in a number of desert studies (Belnap and Eldridge, 2001). As a result, preserving biological soil crusts has been listed as the top management priority in desert regions (Belnap, 2003). The ability to accurately map the spatial distribution and monitor the temporal variation of biological soil crusts with remote sensing technique would greatly assist in this effort (Karnieli et al., 2001).

A number of studies has been conducted to investigate the spectral characteristics of biological soil crusts and its species components with field measurements (Ager and Milton, 1987; Graetz and Gentle, 1982; Jacobberger, 1989; Karnieli and Sarafis, 1996; Karnieli et al., 1996; Karnieli and Tsoar, 1995; Pinker and Karnieli, 1995; Tsoar and Karnieli, 1996). Although these studies revealed the unique spectral features of biological soil crusts, few of them endeavored to apply the field-measured spectral features to map the large-scale biological soil crusts with remotely sensed data. Among the limited studies that aim at mapping biological soil crusts from the perspective of remote sensing, Wessels and Van Vuuren (1986) first used the Landsat TM imagery to discriminate lichen-covered areas from bare ground and vegetated surfaces in Namib desert in SouthWest (SW) Africa. Karnieli (1997) proposed a crust index to map cyanobacteria-dominated biological soil crust with remote sensing data. However, the index cannot be easily grafted to lichen-dominated biological soil crusts, which cover a much larger area than cyanobacteria-dominated biological soil crusts in cool and cold deserts (Belnap, 2003).

In this study, we attempt to investigate the spatial distribution patterns of biological soil crusts by coupling field work and remote sensing. We applied a crust index that was specifically developed for detecting the lichen-dominated biological soil crusts in the Gurbantunggut Desert from the Landsat ETM+ imagery (Chen et al., 2005). As a result, the occurrence of biological soil crusts in the Gurbantunggut Desert was inventoried for the first time. Moreover, the spatial distribution characteristics of biological soil crusts, together with the species distribution patterns at different sand dune locations, were analysed as well.

2. Study area

The study took place in the Gurbantunggut Desert, which is situated in the center of the Jungger Basin in the Xinjiang Uygur Autonomous Region of China, and is the second largest desert in China with an area of 48.8 thousands square km (44°11′–46°20′N, 84°31′–90°00′E, Fig. 1). A wealth of lichen-dominated biological soil crusts can be found in the study area. Recently, due to intensive human activities, such as petroleum extraction and pasturing, biological soil crusts have undergone a significant disturbance. Therefore, it

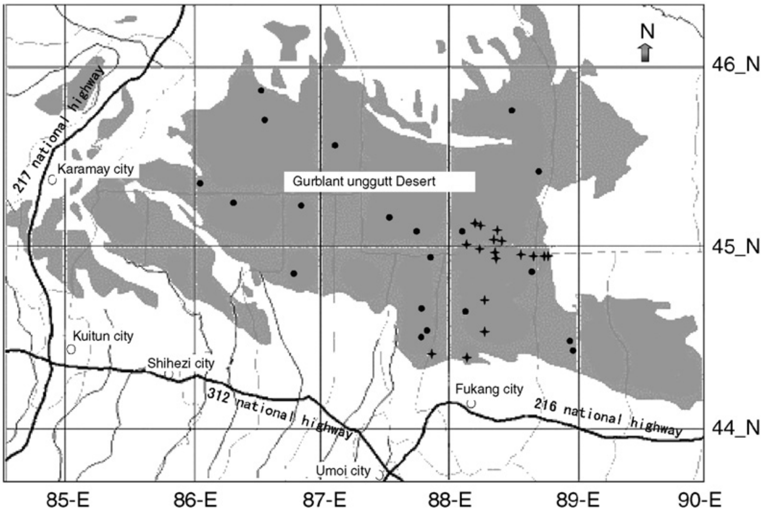

Fig. 1. The Study area and sampling sites distributed in Gurbantunggut Desert.

is necessary to capture current spatial distribution patterns of this important biological resource, as well as provide a viable scheme to implement a long-run monitoring.

Because of the 'blocking effect' of the Himalayan range, moist air currents from the Indian Ocean fail to reach the area, resulting in a vast expansion of arid terrain. Mean annual precipitation is approximately 79.5 mm, falling predominantly during spring. Mean annual evaporation is 2606.6 mm. Average temperature is 7.26 °C. Annual mean active accumulated temperature ($\geqslant$10 °C) is 3000–3500 °C. The mean relative air humidity ranges from 50% to 60%. Wind speeds are greatest during late spring, with an average of 11.17 m/s, and are predominantly WestNorthWest (WNW), NorthWest (NW) and North (N). Most of the sand dunes in the desert are stable and semi-stable. Natural vegetation in the area is dominated by *Haloxylon ammodendron* and *H. persicum* with a vegetation cover of less than 30%. The area is covered by huge and dense semi-fixed sand dunes with stable moisture content. The sand surface is covered by biological soil crusts, which consist of bacteria, cyanobacteria, algae, moss and lichens, and sporadic shrubs. The biological soil crusts on the sand surface of the desert grow favorably during wet, cool periods (fall and early spring) when dew, fog, rainfalls are available to species related to the formation of soil crusts (Du, 1990; Kidron et al., 2002; Zhang et al., 2002).

The study area is characterized by a variety of different soil surface conditions. On dune tops and steep slopes, the sand still shows high aeolian activity and the surface is barely covered by biological soil crusts. The sand in most of the interdune areas and on the lower dune slopes is stabilized. The interdune areas are mainly covered by moss-lichen dominated crusts, and the slopes of sand dunes are mainly characterized by algae-lichen dominated crusts. The biological soil crusts on the slope of sand dunes are primarily flat (i.e. lacking microtopography) with a gray-green coloration, while the biological soil crusts in interdune areas are distributed in dark and elevated patches. Based on physical-chemical and microbiological parameters, three types of biological crusts have been distinguished in the area as algae-dominated crusts, lichen-dominated crusts and moss-dominated crusts (Zhang et al., 2004, Fig. 2).

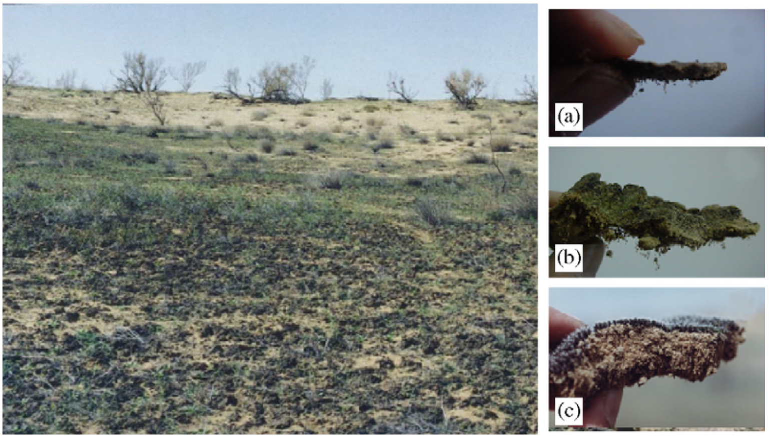

Fig. 2. Appearance of Gurbantunggut Desert (left) and different types of biological soil crusts (a) algae dominated crusts, (b) lichen dominated crusts, and (c) moss dominated crusts.

3. Methods

Three field campaigns were undertaken on October 20, 2002, November 1, 2003, and May 10, 2004 to catch up the growth peak of biological soil crusts in the desert. During the field survey in October 2002, samples of the prevalent land surface such as biological soil crusts, bare sand, plant litter, and dry desert shrubs, were collected at 17 spots in the SouthEast (SE) of the Gurbantunggut Desert where was found to contain the most representative biological soil crusts throughout the desert (Fig. 1, Zhang et al., 2002). In situ spectral reflectance measurements were collected using an MMS-1 portable spectrometer. During the surveys carried out in November 2003 and May 2004, 20 representative sand dunes were chosen to conduct a transect analysis of the species composition and general distribution of biological soil crusts. In addition, 128 GPS points were collected to indicate whether biological soil crusts were present. Such GPS points were used to evaluate the accuracy of biological soil crusts maps derived from remotely sensed data.

3.1. Transect analysis and sample collection

A transect analysis was carried out in the 20 sand dunes that were evenly distributed in our study site (Fig. 1). At each site, seven plots ($1\,m^2$ in area) were positioned on top of sand dunes along three directions: leeward slope of sand dunes, windward slope of sand dunes, and interdune areas, respectively (Fig. 3). In order to acquire original samples, we used a cutting ring to collect the intact biological soil crusts in the quadrate, and shipped them to the nearest lab within a minimum time to take measurements and identify species.

3.2. Development of a new crust index for biological soil crusts mapping

The appearance of the study area and representative biological soil crusts can be checked in Fig. 2. Fig. 4 presents the reflectance spectra of biological soil crusts, bare sand, dry

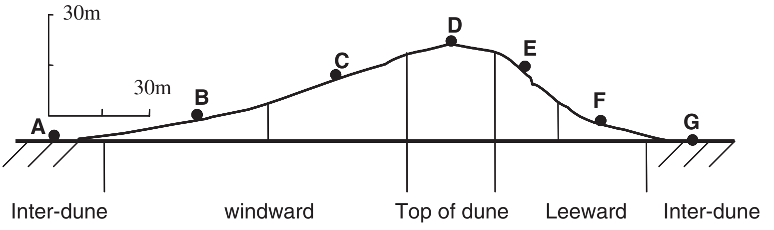

Fig. 3. Collection samples in different locations of sand dune.

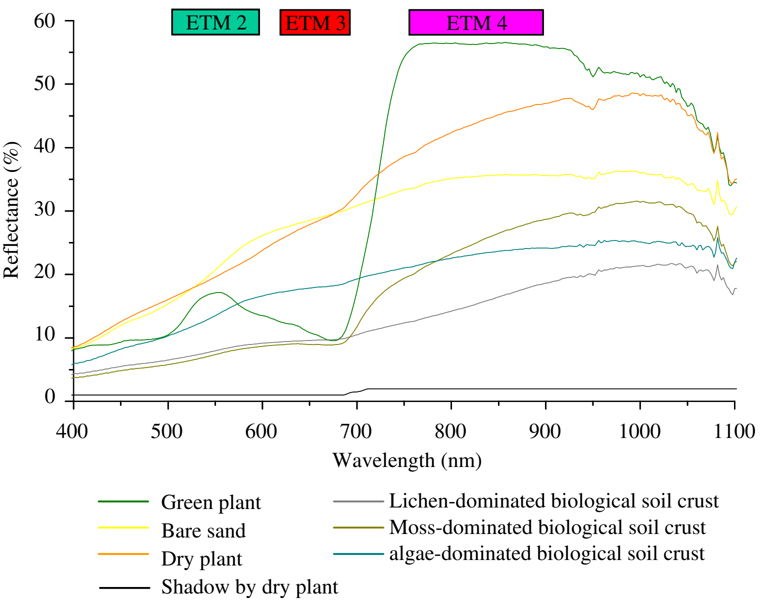

Fig. 4. Reflectance spectra of three biological soil crusts, bare sand, dry plant and its shadow.

plant materials, green plants, and shadows that were measured during November 10–20, 2002 (for further details refer to Chen et al. (2005)). Generally, all curves except those of green plants and shadows exhibit similar spectral features, but differ in overall magnitude of reflectance and the depth of the pigment absorption zone. Compared with bare sand and dry plant material, the three biological soil crusts present a lower reflectance (below 30%) due to their dark surfaces. Another distinctive feature of the reflectance of three crusts is that they exhibit a slightly flattening plateau between 600 and 700 nm as can be ascribed to the absorption by the photosynthetic pigments. In spite of this characteristic absorption feature of green plants, the biological soil crusts do not show the reflectance peak at 550 nm as is often the case with green plants.

Based on our observations, the biological soil crusts show the unique spectral features as follows: (1) the slope between the green and red bands of the biological soil crusts is flatter than those of bare sand, dry plant material, or green plant and (2) the biological soil crusts have a much lower reflectance at visible and near infrared bands than those of bare sand, dry plant material or green plant. To inherit the above findings, we developed a biological soil crust index (BSCI) with an aim to exaggerate the difference between biological soil crusts and the background of bare sand, dry plant material or green plant (Chen et al., 2005). Specifically, the proposed BSCI is defined as:

$$\mathrm{BSCI} = \frac{1 - L \times \left| R_{\mathrm{red}} - R_{\mathrm{green}} \right|}{R_{\mathrm{GRNIR}}^{\mathrm{mean}}}, \tag{1}$$

where R_{green} and R_{red} are, respectively, the reflectance of the green and red bands, which correspond to band 2 and 3 for the Lands at ETM+ sensor. L is an adjustment parameter to amplify the absolute difference between R_{green} and R_{red}. In case the numerator gets a negative value, L is restricted within the range 2–4. In this study, we assigned 2 as the value of L in accordance to our observations. $R_{\mathrm{GRNIR}}^{\mathrm{mean}}$ is the mean reflectance of green, red, and the near infrared band, which subsequently refers to band 2, 3, and 4 for the Landsat ETM+ sensor. In order to remove the effect due to changes in illumination geometry (Huang et al., 2000), all the reflectance elements involved in the calculation is converted to surface reflectance, which ranges from 0 to 1.

Specifically, the rationale underneath BSCI is given as follows. Since the value of ($R_{\mathrm{green}} - R_{\mathrm{red}}$) for biological soil crusts will be much lower than that of bare sand, dry plant material, or green plant, by subtracting it from 1, the numerator of the BSCI for biological soil crusts will end up with a relatively larger value as opposed to other types. With regards to the denominator, since biological soil crusts are associated with a uniformly low reflectance value throughout the visible and near infrared bands, $R_{\mathrm{GRNIR}}^{\mathrm{mean}}$ for the soil crusts will stay at a low value. Compounding the nominator and denominator, the BSCI will present a higher value for biological soil crusts than other cover types.

However, given the coarse spatial resolution of the Landsat ETM+ (i.e. 30 m), the BSCI value for each pixel would largely depend on the percent coverage of biological soil crusts within the IFOV. We have found that BCSI values for biological soil crusts fell in a range, which were bounded by two thresholds, a lower-bound threshold at which the crusts cannot be distinguished from the background, and an upper-bound threshold at which the coverage of biological soil crusts reach 100%. Employing a radiative transfer simulation for Landsat ETM+ under different atmospheric conditions, we obtained the lower and upper thresholds of BSCI as 3.69 and 6.59 were Landsat ETM+ data adopted.

To map biological soil crusts with the BSCI index in the Gurbantunggut Desert, four scenes of Landsat 7 ETM+ image data, (path/row: 142/29, 18 October 2002; path/row: 142/28, 10 October 1999; path/row: 143/28, 7 November 2001; path/row: 143/29, 17 September 2002) were acquired to cover the whole Gurbantunggut Desert. The Landsat ETM+ images were geometrically corrected to the UTM projection. Likewise, the raw digital numbers (DN) of the Landsat ETM+ image were converted to reflectance values according to the method described in the Landsat 7 Science Data Users' Handbook (Irish, 1998). Specifically, the atmospheric correction method for the Landsat TM data as proposed by Ouaidrari and Vermote (1999) was employed to convert the top-of-atmosphere (TOA) reflectance to surface reflectance. This correction method is based on the 6S radiative transfer code and can make corrections for atmospheric and adjacency effects.

The BSCI was then calculated for each pixel of Landsat ETM+ image based on the surface reflectance. The biological soil crusts pixels were labeled if their BSCI values fall in the range 3.69–6.59. On the other hand, the pixels with BSCI values less than 3.69 were identified as bare sand and dry plants while the pixels with BSCI values over 6.59 were identified as clouds and tall-dune shadow areas. Because biological soil crusts did not exist in agricultural land, croplands were excluded by visual interpretation. A final result covering the whole Gurbantunggut Desert was obtained by mosaicing the results classified from four Landsat ETM+ scenes.

4. Results and discussions

4.1. Species composition and general distribution of soil crusts in different sand dune locations

Based on our observations from transect investigations in the twenty sand dunes, the algae species are most abundant in the South, followed by the Central part of the desert. In contrast, the algae species are very few in the West and East where hardly any biological soil crusts can be found. Some species are not selective upon locations and are the most common species in the desert, such as *Microcoleus paludosus*, *M. vaginatus*, *Xenococcus lyngbyge*, *Chroococcus turgidus* var. *solitarius,* and so on. Most species are selective upon locations and only occurred in particular locations of sand dunes. For example, in the interdune area, species such as *Anabaena azotica*, *Lyngbya martensiana*, *Stigonema ocellatum*, *Amphora ovalis*, *Chlamydomonas mutabilis*, and *Calothrix stagnalis* are mostly discovered. However, on the top of sand dunes, species such as *Phormidium faveolarum*, *Microspora pachyderma*, *Oscillatoria princes,* and *Scenedesmus bijuga* are usually present. The windward slopes of sand dunes are heavily dominated by cyanobacteria such as *M. paludosus*, *M. vaginatus*, *Scytonema crispum*, *Anabaena azotica,* and *Scytonema crispum*. The leeward slopes of sand dunes, however, are heavily dominated by green algae such as *Chlorella vulgaris*, *Chlorococcum humicola*, *Microspora pachyderma*, *Palmellococcus miniatus*, *Chlamydomonas mutabilis,* and *Scenedesmus bijuga*.

The rugose biological soil crusts in this desert are heavily dominated by lichens, with occasional mossy patches in interdune areas. Soil lichens occur in dense patches in the Gurbantunggut Desert. The most common lichens include *Collema tenex*, *Psora decipiens*, *Xanthoria elegans*, *Acarospora strigata*, and *Lecanora argopholis*. Other less common lichens include *Diploschistes muscorum*, *Heppia lutosa*, *Catapyrenium* sp., and *Caloplaca songoricum*. The lichens in the desert usually appears black, white, brown, yellow or blue due to different species. Lichens-dominated biological soil crust is the primary type of the biological soil crusts in the desert. The lichens in the west slope of sand dunes grow better than those in the east slope. Going from the slope of sand dunes to the interdune areas, lichen-dominated biological soil crusts develop flakily and cover a large area. Generally, lichen-dominated biological soil crusts develop best in South, followed by the central and north parts. In the West of the desert, they develop in small areas only in isolated regions in interdune areas and almost disappear in the East.

Soil moss species are limited, with *Tortula desertorum* and *Bryum argenteum* being the most common in the desert. Other frequent mosses include *Crassidium chloronotos*, *Tortula muralis,* and *Bryum capillare*. Most mosses can be found only under the canopy of vascular plants, such as *Haloxylon persicum* and *Ephedra distachya*, which provide protections from sediment burial and strong sunlight. In these microhabitats, water can be sustained for a long time, UV light can be decreased, and temperatures are more favorable for the moss growth. Unlike deserts in the United States or Australia, however, liverworts are quite uncommon even under such canopies. Spatially, the lichen and moss crusts are mainly distributed in the south of the Gurbantunggut Desert. The crust cover becomes sparse in the central and northern parts of the desert, and are absent in the western and eastern parts of the desert.

In the Sonoran desert, Great Basin deserts and areas of Australia, although vascular plant species and climate vary greatly between theses regions, the same soil lichens (*Collema, Placidium, Psora*) dominate the biological soil crusts. While most algae, lichens and mosses are cosmopolitan, a few are endemic and may be common on a local and regional level (Belnap and Eldridge, 2001).

4.2. The spatial distribution pattern of biological soil crusts

Fig. 5 shows the spatial distribution of biological soil crusts in the study area. The accuracy of the classification was evaluated with aids of the field survey data in two classes: crusted and non-crusted. Table 1 shows an error matrix that's constructed from 128 GPS points obtained in the field survey in October 2002, November 2003, and May 2004. A κ coefficient of 0.76 and an overall accuracy of 88.2% were achieved, suggesting an acceptable result for the purpose of mapping biological soil crusts at such a large-scale study.

By examining Fig. 5, the distribution of biological soil crusts in the study area can be summarized in the following two aspects: (1) the desert possesses the most abundant

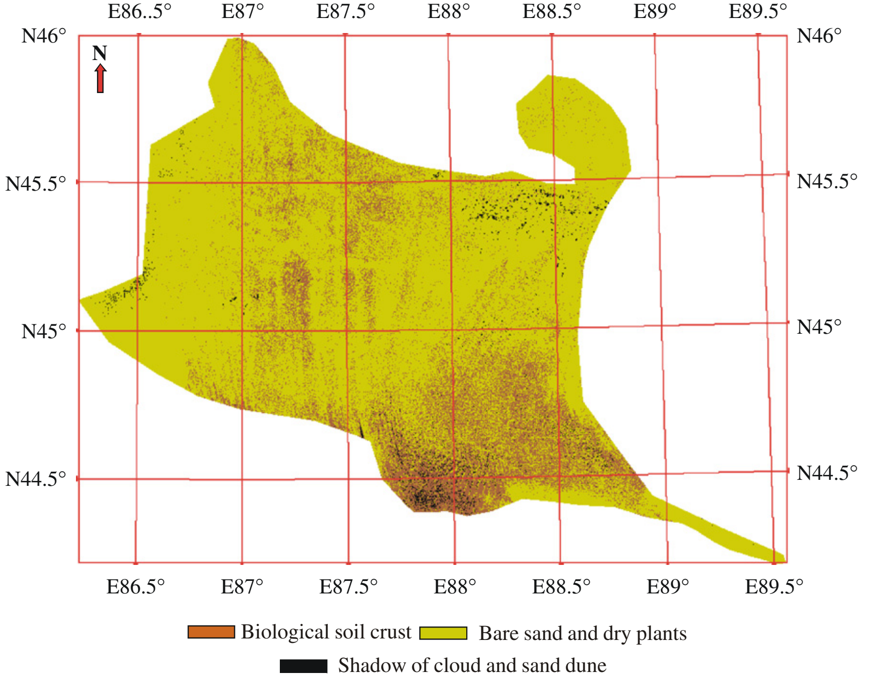

Fig. 5. The spatial distribution of biological soil crusts in the Gurbantunggut Desert.

Table 1
Error matrix for 'crusted/uncrusted' detection by 128 GPS points obtained in the field survey

	Reference data			
	No crusted points	Crusted points	Sum	Commission error
Detected results				
No crusted points	61	5	66	7.58
Crusted points	10	52	62	16.13
Sum	71	57	128	
Omission error	14.08	8.77		

Overall accuracy = 88.2%; κ coefficient = 0.76

biological soil crusts in the South, followed by the Central and North. In the East, ground surface is characterized by shifting or semi-shifting sand as a whole. No evidence of biological soil crusts was found. The distribution of biological soil crusts developed in the central and west of the desert is discontinuous and restricted in a small area. The biological soil crusts can be hardly found from the Shixi oil field to the west of Mosowan town. (2) Biological soil crusts are continuously distributed in the South, but its distribution pattern becomes patchier in the North, West, and East. Basically, the distribution patterns of biological soil crusts observed from the Landsat ETM+ images agree with our field survey observations. However, the cause of such distribution is still unknown, and needs further investigation in the future. Counting the number of classified biological soil crusts pixels reveal that biological soil crusts cover 28.7% of the land in the study area. However, it is worth mentioning that the crusts' coverage may be underestimated since detection of crusts from the Landsat ETM+ imagery is viable only if crusts constitute more than 33% of the IFOV of the Landsat ETM+ sensor.

The biological soil crusts cover vast surfaces in the arid and semi-arid deserts all over the world. Some studies have used remote sensing to detect and map their distributions and functioning on a large scale (Burgheimer et al., 2006; Chen et al., 2005; Karnieli et al., 2001; Orlovsky et al., 2004; Qin et al., 2002; Qin et al., 2005; Schmidt and Karnieli, 2000). Several environmental factors contribute to the distribution of biological soil crusts on the large scale, such as elevation, soil and topography, disturbance, timing of precipitation, vascular plant community structure, ecological gradients, and microhabitats (Eldridge, 1993; Hansen et al., 1999; Harper and Marble, 1988; Johansen, 1993; Kleiner and Harper, 1977; Kaltenecker et al., 1999; West, 1990). The vigor of biological soil crusts is mainly attributed to water availability. Biological soil crusts are relatively rare in the North of the study area, but become more common in the South. Such a distribution pattern can be attributed to the precipitation patterns, which keep decreasing from the South to North in this desert. Although water condition served as the main constraint that determine the distribution of biological soil crusts, other factors, such as sand grain size, mineral composition and pH value, still play some roles in shaping the distribution of biological soil crusts. A previous study showed it is the case that different locations of the desert come with a different amount of sand grain size, mineral composition, and pH values (Qian et al., 2003). This study presented the spatial distribution patterns of biological soil crusts in the Gurbantunggut Desert for the first time. A continued effort is currently under way to analyse how and at what extents that different environmental factors control the distribution and development of biological soil crusts in the Gurbantunggut Desert.

5. Conclusions

The biological soil crusts found in the Gurbantunggut Desert appeared to be heavily dominated by lichens, occurring in dense patches, with occasional moss patches. The distribution of these crusts differed among locations. Species composition of the biological soil crusts also differed with developmental stages. The windward slopes of the sand dunes were heavily dominated by cyanobacteria while the leeward slopes of sand dunes were covered by green algae. The lichen crusts mainly grow on the lower end of the slope of sand dunes as well as in the interdune areas. Soil moss species could be only found under canopies of vascular plants.

Spatially, the lichen and moss crusts were found mainly in the Southern part of the Gurbantunggut Desert. The crust cover became sparser to the North and was absent in the West and East parts of the desert. Classification from the Landsat ETM+ imagery revealed that biological soil crusts were covering 28.7% of the land in the study area with a risk of underestimation as can be ascribed to the crude spatial resolution of the ETM+ imagery.

Acknowledgments

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