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Surface roughness response of biocrust-covered soil to mimicked sheep trampling in the Mu Us sandy Land, northern China

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ABSTRACT

Surface roughness plays an important regulatory role in the interactions and feedback between the soil surface and atmospheric systems. However, information regarding the response of surface roughness to trampling disturbances caused by sheep grazing is limited, especially in sandy soils covered by biocrust. This study investigated the covariations in the roughness, coverage and shear strength of cyanobacterial crust (CC), algae-lichen mixed crust (LC) and moss crust (MC) on both the semi-fixed and fixed dunes at the southern edge of the Mu Us Sandy Land, northern China, under various trampling intensities using field studies and mimicked sheep trampling disturbances. The results showed that the surface roughness of semi-fixed and fixed dunes decreased after an initial increase with increasing trampling intensity, and the surface roughness of the fixed dunes was higher than that of the semi-fixed dunes. In addition, with the increasing trampling intensity, the maximum surface roughness (R_{max}) and its corresponding trampling intensity of the biocrust-covered soils at different development stages followed the order of CC, LC, and MC. The grazing intensity (G) corresponding to R_{max} values in both the semi-fixed and fixed dunes at different development stages of biocrust was 9.6 to 14.4 and 11.1 to 14.4 animal unit day/ha, respectively. The biocrust coverage and shear strength decreased exponentially with increasing trampling intensity and significantly affected the sensitivity of surface roughness to changes in trampling strength. Moderate grazing (grazing intensity less than G) was beneficial for increasing the surface roughness of biocrust-covered sandy land. Increased surface roughness has positive and negative impacts on the ecological and hydrological functions of biocrust-covered soil. To minimize the negative effects of moderate grazing on surface soil, the dune fixation degree, biocrust development level, trampling time and interannual precipitation variability should be considered. This study highlighted the role of grazing management in enhancing the surface roughness and associated ecosystem functions of semiarid regions similar to the Mu Us Sandy Land.

1. Introduction

Surface roughness describes the micro-relief of the soil surface at the centimeter to decimeter scale (Bullard et al., 2018). Changes in surface roughness not only affect surface processes, such as wind and water erosion (Kidron et al., 2012; Chamizo et al., 2017), but also play an important regulatory role in the interaction and feedback processes between the soil and atmospheric systems (Rodríguez-Caballero et al., 2012; Bullard et al., 2018). Compared with natural processes, the impacts of human activities on surface roughness are more likely to cause changes in the surface ecological functions (Viles et al., 2008). However, there are limited studies on the complex and nonlinear relationship between surface roughness changes caused by human activities and its ecological functions (Viles et al., 2008).

Biocrust is an important surface feature in dryland areas. Biocrusts currently cover approximately 12% of the Earth's terrestrial surface (Rodriguez-Caballero et al., 2018). The formation and development of biocrusts on the surfaces of dunes significantly change the surface roughness and are directly or indirectly involved in many ecological and hydrological ecosystem processes, such as the dust deposition distribution (Williams et al., 2012), surface stability (Zhang et al., 2006; Kidron et al., 2009), water infiltration (Chamizo et al., 2012; 2017), surface runoff (Kidron, 2007; Rodríguez-Caballero et al., 2012; Kidron et al., 2012), dew formation (Kidron et al., 2002; Jia et al., 2014), greenhouse gas emissions (Grant et al., 2017), microclimate (Yates et al., 2000), seed settlement, and vascular plant germination (Prasse

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and Bornkamm, 2000; Langhans et al., 2009). When biocrust is mechanically disturbed, the roughness of the soil surface changes significantly and affects its ecological functions (Bello et al., 2006; Jia et al., 2014). Therefore, surface roughness has become one of the most crucial physical indicators in evaluating ecosystem stability and the degree of mechanical disturbance because of its intuitive and sensitive characteristics (Nash et al., 2003; Belnap et al., 2008).

The surface roughness of biocrust-covered soil is not only affected by its successional stages but is also sensitive to external disturbances, such as trampling, sand burial and fire, resulting in significant changes in the surface ecological functions (Belnap, 2006; Jia et al., 2014). Grazing is one of the most common trampling disturbances in arid areas (Zhang et al., 2013), and it affects nearly half of the world's arid and semiarid areas (Eldridge et al., 2017). Biocrust are more sensitive to trampling disturbances due to grazing compared to vascular plants because of their micro and fragile nature (Concostrina-Zubiri and Martínez, 2014). Studies on the effects of trampling disturbance due to grazing on biocrusts are mainly focused on the soil surface cover (Golodets and Boeken, 2006), distribution (Zhang et al., 2013), moss growth (Csotonyi and Addicott, 2004), wind erosion (Wang et al., 2009), carbon and nitrogen cycles (Liu et al., 2009; Thomas, 2012), water infiltration (Chamizo et al., 2012; Shi et al., 2017), and microbial diversity (Olivera et al., 2016; Eldridge et al., 2017; Bao et al., 2019) and its effects on functional diversity (Bello et al., 2006; Mallen-Cooper et al., 2018). Few studies have focused on the mechanism underlying the surface roughness response of biocrust-covered soil to trampling disturbances caused by grazing and subsequent variations in the associated ecological functions.

The Mu Us Sandy Land is one of the four major sandy lands and a typical vegetation fixation sandy land in China (Wu et al., 2012). With the ecological restoration of vegetation, biocrusts have been widely developed on the surface of sand dunes, although they are frequently disturbed by trampling due to grazing (Zhang et al., 2013). Although grazing is a common practice in the area, the effect of trampling disturbances due to sheep grazing on the surface roughness of biocrust-covered soil is rarely explored. Moreover, the complex and nonlinear relationships between the variations in the roughness of biocrust-covered surfaces induced by the human activities and subsequent changes in the ecological functions are largely unknown. However, these relationships represent a fundamental basis for the scientific management of sandy ecosystems. Therefore, we asked the following questions: 1) Will trampling disturbances lead to a continuous reduction in the surface roughness of biocrust-covered sandy soil? 2) Is there any difference in the surface roughness response of biocrust-covered soil to trampling at different developmental stages? If yes, what is the response mechanism? 3) Are there possible differences in the surface roughness of fixed and semi-fixed dunes due to sheep grazing? We selected different types of biocrusts (cyanobacterial crust (CC), algae-lichen mixed crust (LC) and moss crust (MC)) on the surfaces of fixed and semi-fixed dunes in the Mu Us Sandy Land to address these questions. The covariations in biocrust-covered soil surface roughness, shear strength, and biocrust coverage were measured by field investigations and simulations of sheep trampling disturbance. The objectives of this study were to 1) discover the patterns and mechanisms of the responses of biocrust-covered soil surface roughness to trampling disturbance due to grazing; 2) determine the moderate grazing intensity for different development stages of biocrust on semi-fixed and fixed dunes; and 3) provide a basis for the ecological rehabilitation and scientific management of the Mu Us Sandy Land and similar ecosystems.

2. Material and methods

2.1. Description of the study area

The study area (108°50′E, 37°38′N; 1350 m elevation) is located on the southern edge of the Mu Us Sandy Land, Shaanxi Province, China (Fig. 1). The study site is a typical transitional area extending from the Ordos Plateau to the Loess Plateau in northern Shaanxi Province and has a semiarid climate. The mean annual precipitation and evaporation are 395 mm and 2485 mm, respectively, and evaporation is approximately six times greater than precipitation, which mainly occurs in summer (June to August). The main wind direction of the study area is from the northwest, and these winds mainly occur in March-May of each year. Therefore, the rainy season and monsoon season of the study area is June to August and March to May, respectively (Wu et al., 2012). The landscapes in the study area are mobile, semi-fixed, and fixed dunes and lake basin beaches. The mechanical composition of dune sediments is mainly fine sand (Wu et al., 2012). The study area is in the warm temperate grassland zone. The vegetation coverage in the study area is 28–50%, and it is dominated by *Artemisia ordosica* Krasch., *Agriophylium squarrosum* (L.) Moq, *Corispermum puberulum* IIjin and *Psammochloa villosa* (Trin.) Bor. The main artificial vegetation is *Populus simonii* Carr, *Salix psammophila* C. Wang et Ch. Y. Yang, *Hedysarum mongdicum* Turcz Var., *Amorpha fruticosa* Linn. and *Sabina vulgaris*.

Biocrusts have developed extensively on the surfaces of the fixed and semi-fixed dunes in the study area. The biocrust coverage of the fixed dunes is more than 65% where MC is the dominant type of biocrust and only a small portion is covered by CC. The surface biocrust coverage of semi-fixed dunes ranges from 45 to 65%, and CC is the primary biocrust while MC and LC account for lower proportions. The characteristics of biocrust on the surface of the fixed and semi-fixed dunes in the study area are shown in Table 1.

Sheep farming represents a major component of the economy for the Mu Lu Sandy Land; hence, grazing is frequently practiced in the study area outside of non-grazing areas, which has resulted in the disturbance of more than 60% of the biocrusts to a varying degree. In addition, nearly 35% of the biocrust-covered surface areas are exposed or even buried by sand due to the frequent trampling of sheep.

2.2. Field investigation of sheep hoof footprints in the study area

In May 2018, three parallel transects with lengths of approximately 300 m were randomly arranged in the study area where biocrusts were well developed and disturbed partially by trampling due to grazing. The horizontal distance between transects was at least 50 m to ensure the representativeness of the sample plots. Quadrats (20 × 20 cm) were established randomly every 10–15 m along transects (to avoid shrubs and plants). A total of 60 quadrats were observed in three parallel lines (20 quadrats in each line). A total of 80 measurement points were investigated over three transects. In each quadrat, one to two representative footprints (a single footprint with intact biocrust around it) of sheep hooves were selected to measure their trampling area and depths on the soil surface. A digital camera placed directly above the trampling area was used to photograph the trampling area using a ruler as a reference. The trampling area was then calculated by computer-aided design (CAD) software (version 2011). The trampling depth was measured directly by a surface difference ruler (Fig. 2). The mean recorded trampling area and depth were 53.75 ± 10.40 cm^2 and 22.81 ± 4.27 mm, respectively, which were used as the basis for the mimicked sheep trampling disturbance treatment in the later stages of the experiment.

2.3. Mimicked sheep trampling treatment

From July to August 2018, representative fixed and semi-fixed dunes with different development stages of biocrusts were selected for the mimicked sheep trampling disturbance treatment. No grazing activity was observed in the area; hence, biocrusts were well preserved. Where possible, the biocrust quadrats (20 × 20 cm) were randomly established in areas with less topographic fluctuations, such as the foot of windward slopes and interdune areas of dunes (100% biocrust coverage in each quadrat before the mimicked sheep trampling

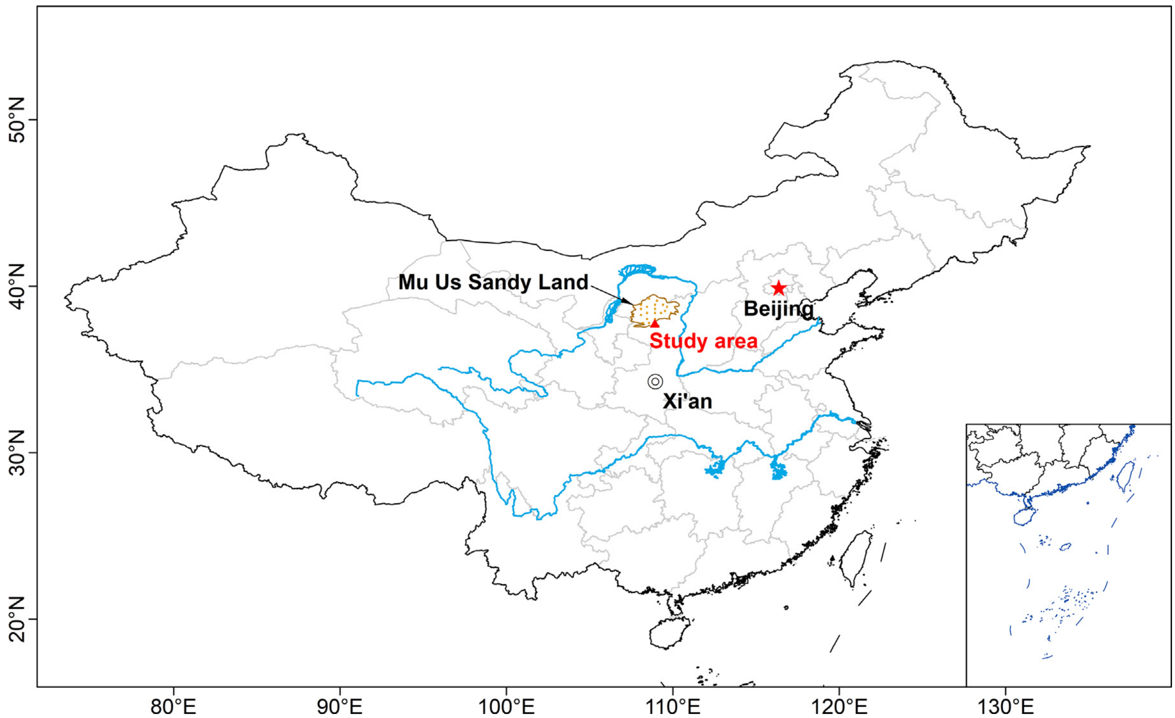

Fig. 1. Geographical map of the study area.

disturbance) to determine the initial surface roughness of biocrust-covered soil. Subsequently, sheep hooves were used to simulate animal trampling disturbance in the quadrat. The mimicked sheep trampling area and depth were close to the mean trampling area and depth recorded during field investigations (see Section 2.2). The mimicked sheep trampling disturbance by sheep hooves was randomly conducted within each quadrat five times as one trampling round (five rounds of multiple mimicked sheep trampling in the quadrat). Repeated mimicked trampling disturbances were conducted until the coverage of biocrust in the quadrat was reduced to zero. Compared with the larger quadrats, the smaller quadrats (20 × 20 cm in size) were more sensitive to mimicked sheep trampling disturbance and were able to detect the slight variations of surface roughness at the beginning of the mimicked sheep trampling disturbance. The quadrat size adopted in this study accurately reflects the variation in surface roughness of biocrust-covered sandy soil because the quadrat was big enough to fit a single hoof despite being slightly too small for a sheep. Negligible rainfall (< 1 mm) occurred 10 days before the mimicked sheep trampling disturbance, which helped to minimize the influence of soil moisture content differences on the surface roughness. When the influence of soil moisture on the variations of surface roughness is neglected, the crust type and repeated mimicked sheep trampling (one trampling round) represent the two influencing factors. The crust types can be divided into two types of dune (fixed and semi-fixed) and three types of crust (CC, LC and MC) on the surface of dune (6 levels in total). Eight to nine sets of repeated mimicked trampling disturbance were set for different types of biocrusts (CC and LC set 8 rounds of trampling and MC set 9 rounds of trampling; the biocrust coverage was reduced to zero after repeated mimicked trampling). Fifty rounds of repeated trampling treatments were performed in total. Each treatment had 3 replications, and 150 rounds of repeated mimicked trampling treatments were performed in 18 quadrats. At the end of each trampling round, the surface roughness in any direction of the quadrat was measured six times by chain methods (see Section 2.4) to identify the surface roughness changes caused by this round of mimicked sheep trampling disturbance. Following each round of mimicked sheep trampling disturbance, the biocrust coverage and surface shear strength were measured and then followed by another round of trampling disturbance. Selected biocrusts for mimicked sheep trampling disturbance were mostly scattered in the open spaces between the vegetation, which were mainly spot structured or banded shrubs. The coverage of herbaceous plants was usually < 5%. Therefore, the effect of vegetation on variations of surface roughness was neglected during the mimicked sheep trampling disturbance treatment.

Table 1
General characteristics of the surface biocrust of fixed and semi-fixed dunes in the study area.

Sand dune	Type	Thickness (mm)	Shear strength (kg/cm^2)	Organic carbon (%)	Particle size distribution (%)			Dominant species
					Sand	Silt	Clay	
Semi -fixed dune	CC	5.2 ± 0.5 b	0.5 ± 0 c	0.3 ± 0.1 b	91.8 ± 0.5 a	6.3 ± 0.4 c	1.9 ± 0.1 b	I, III
	LC	6.4 ± 0.4 b	0.8 ± 0 b	0.4 ± 0.1 b	89.6 ± 0.7 a	8.3 ± 0.1 b	2.1 ± 0.8 b	II, IV
	MC	10.7 ± 0.9 a	1.1 ± 0.1 a	1.1 ± 0 a	75.7 ± 0.9b	20.3 ± 0.5 a	4.0 ± 0.4 a	V, VI
Fixed dune	CC	6.4 ± 0.4 b	0.6 ± 0.1 b	0.4 ± 0 b	91.2 ± 0.5 a	6.7 ± 0.5 c	2.1 ± 0.2 b	I, II, III
	LC	6.8 ± 0.4 b	1.0 ± 0.1 b	0.4 ± 0 b	88.8 ± 0.2 a	8.6 ± 0.2 b	2.6 ± 0.3 b	II, III, IV
	MC	11.3 ± 0.6 a	1.6 ± 0.2 a	1.1 ± 0.1 a	74.9 ± 1.2 b	20.7 ± 0.6 a	4.4 ± 0.7 a	VII

Note: The data in the table are the mean ± SE, $n = 3$. Different small letters of the same column for different types of biocrust represent significant differences at the 0.05 significance level. CC, LC and MC represent cyanobacterial crust, algae-lichen mixed crust and moss crust, respectively. I. *Microcoleus vaginatus* Gom.; II. *Oscillatoria* spp.; III. *Lyngbya* spp.; IV. *Collema* spp.; V. *Bryum dichotomum* Hedw.; VI. *Bryum argenteum*; VII. *Didymodon vinealis* (Brid.) Zander.

Fig. 2. Measurement of the trampling area (left) and depth (right) of footprints of sheep hooves.

2.4. Methods of measurements of surface roughness, biocrust coverage and shear strength

Surface roughness was measured by the chain method (Saleh, 1993). The measurements were based on the principle that the straight-line segment between two points is the shortest and the distance increases as the surface roughness increases between two points. When a chain of a certain length (C_1) was placed on the surface of the intact or disturbed biocrust, its horizontal length (C_2) decreased with increasing biocrust-covered surface roughness. The variations of surface roughness under different trampling intensities are determined by the reduction of the rate of chain length in any six directions of the quadrats after each round of mimicked trampling disturbance. The length of the chain used in this study was 18.5 cm with single increments of 1.2 mm. The surface roughness index of the biocrust was calculated using formula 1:

$$C_r = (1 - C_2/C_1) \times 100 \tag{1}$$

where C_r represents the roughness in any direction, C_1 represents the length of a given chain (cm), and C_2 represents the horizontal length after the chain is placed on the surface (cm).

Biocrust coverage was measured by the point sampling frame (Li et al., 2017). A small quadrat of 20 × 20 cm was divided into 400 1 × 1 cm grids. At the end of each trampling treatment, the square frame was placed vertically above the quadrat to observe whether there were cryptogam plants in each grid. The biocrust coverage was calculated according to the number of times cryptogam plants appeared in the quadrat (Li et al., 2017).

The soil surface shear strength was measured by a pocket soil shear tester (Eijkelamp Corporation, Netherlands). The tester's cross headings (diameter of 48 mm) were pressed into the soil surface, and then the soil shear tester was twisted. When the shear strength of the surface soil exceeded the shear resistance, data were recorded. According to the size of the cross headings, the data were converted using a coefficient of 0.2.

2.5. Data analysis and processing

Using Origin 8.0 software (Origin Lab, USA), a nonlinear regression analysis was used to evaluate the variation in surface roughness with trampling intensity. The Lorentz function was used to calculate the maximum surface roughness (R_{max}) and its corresponding trampling intensity (T) for the different development stages of biocrusts on the surface of the fixed and semi-fixed sand dunes. To achieve higher surface roughness, we used the concept of moderate trampling intensity based on the T value. When the trampling intensity was less than T, it was considered moderate trampling, and when trampling intensity was greater than T, it was considered severe trampling.

The grazing intensity (G) was calculated based on T. To calculate G on the larger scale, the T value determined by mimicking sheep trampling in the quadrat was converted to the hectare scale. The trampling intensity at the hectare scale was defined with T_1, and the G was determined using the following formula:

$$T_1 = G \times 4 \times Unit \times Day \tag{2}$$

where T_1 is the number of hoof prints (footprint/ha); G is the grazing intensity (animal unit day/ha); 4 is the number of hooves/sheep; *Unit* is the trampling frequency based on field investigation results of grazing in the study area; and *Day* is ca. 30 days in each year; in addition, the time required for each trampling event was ca. 5 s, and the trampling activity lasted nearly 4 h per day (Golodets and Boeken, 2006; Zhang et al., 2013). Based on G, we suggested that the moderate grazing intensity occurs when the grazing intensity was less than G, and the severe grazing intensity occurs when the grazing intensity was greater than G.

A linear regression analysis was performed to establish the relationships of surface roughness with biocrust coverage and the shear strength of different types of biocrust-covered fixed and semi-fixed dunes. The general characteristics of the different types of biocrusts on the fixed and semi-fixed dune surfaces were analyzed by the least significant difference (LSD) method in a one-way analysis of variance (ANOVA) using SPSS 23 software (SPSS, Chicago, IL, USA) ($P < 0.05$). The results were visualized using Origin 8.0 software.

3. Results

3.1. Variations in the surface roughness of biocrust-covered soil as the trampling intensity increased

The surface roughness of both fixed and semi-fixed dunes covered with the different development stages of biocrust decreased after an initial peak as the trampling intensity increased (Fig. 3). After multiple trampling (15–20 times), the surface roughness of biocrust on the fixed and semi-fixed dunes reached its maximum value, which was 1.6–3 times greater than that before the trampling disturbance. Further increases in the trampling intensity resulted in a decline in the surface roughness of both dunes. The surface roughness was close to the level before the trampling disturbance after 40–45 trampling events.

The surface roughness of the biocrust-covered soil with different development stages on the fixed and semi-fixed dunes also varied as the trampling intensity increased. The surface roughness of the fixed dunes was higher than that of the semi-fixed dunes when the trampling intensity increased. The rate of increase of the surface roughness of the semi-fixed dunes was higher than that of the fixed dunes, whereas the rate of decrease of surface roughness of the fixed sand dunes was lower than that of the semi-fixed dunes under increases in trampling intensity

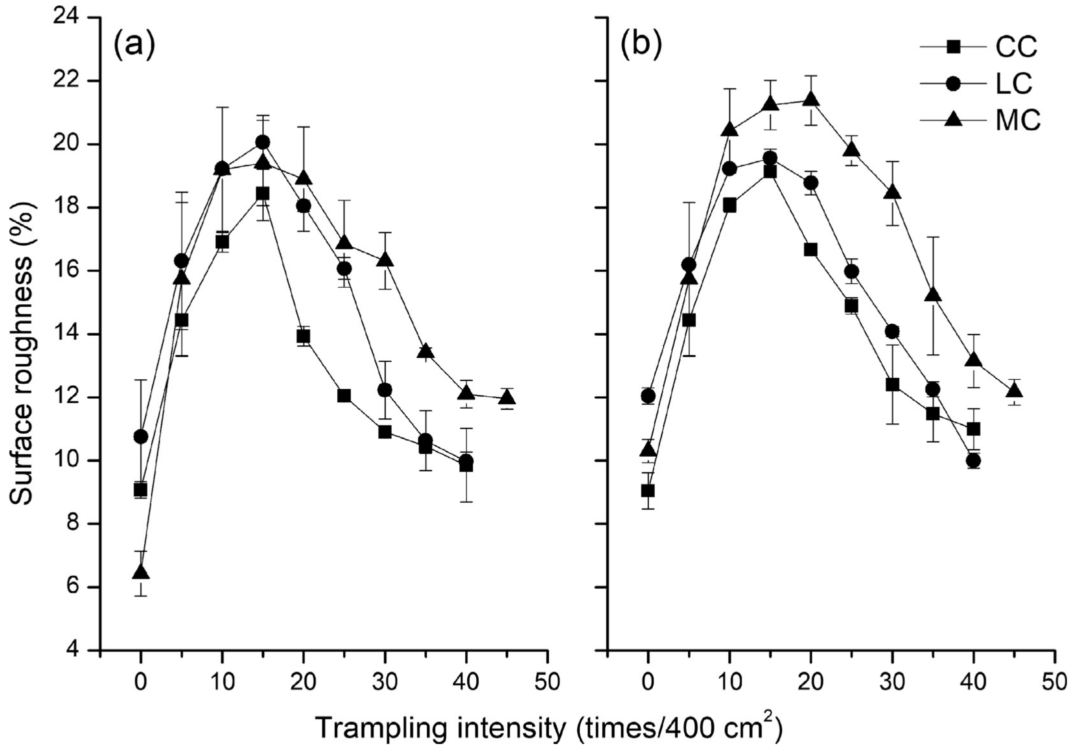

Fig. 3. Changes in the surface roughness of biocrust-covered soil with the increasing trampling intensity in semi-fixed (a) and fixed dunes (b) with different stages of development. CC, LC and MC represent cyanobacterial crust, algae-lichen mixed crust and moss crust, respectively. Bars represent standard errors, $n = 3$.

(Fig. 3).

The variation of surface roughness of soil covered with different developmental stages of biocrust differed as the trampling intensity increased. As the trampling intensity increased, the surface roughness of the MC was generally greater than that of the CC. The rate of increase of surface roughness of the MC was higher than that of the CC and LC, and the rate of decrease of the surface roughness of the MC was always lower than that of the CC and LC. The disappearance of the MC from the surface of the fixed and semi-fixed dunes required more trampling disturbances (Fig. 3).

3.2. R_{max}, *T and G in semi-fixed and fixed dunes at different development stages of biocrust*

The surface roughness of both the semi-fixed and fixed dunes covered with different development stages of biocrust showed a single peak as the trampling intensity increased, and the non-linear fitting results were significantly correlated ($P < 0.001$) (Table 2). The R_{max} and T values were higher in the fixed dunes than the semi-fixed dunes. The R_{max} and T values of the biocrust-covered surfaces at different development stages followed the order CC < LC < MC. Based on the T in the quadrat, the G of the soil surface covered by biocrust at different developmental stages on semi-fixed and fixed dunes was 9.6–14.4 and 11.1–14.4 animal unit day/ha, respectively (Table 2). Thus, the moderate grazing intensity should be controlled within 9.6–14.4 and 11.1–14.4 animal unit day/ha at the different developmental stages of biocrusts on semi-fixed and fixed dunes, respectively.

3.3. *Variations in biocrust coverage and shear strength with increases in trampling intensity and their relationships with surface roughness*

As the trampling intensity increased, the biocrust coverage and the surface shear strength of both the fixed and semi-fixed dunes decreased exponentially at all stages of development (Fig. 4). The biocrust coverage and surface shear strength on the fixed dunes were higher than that of the semi-fixed dunes, whereas their reduction rate on the semi-fixed dunes was greater than that on the fixed dunes when the trampling intensity increased. Similarly, the coverage and surface shear

Table 2

Fitting results of the variation of surface roughness with trampling intensity and calculated values of R_{max}, T and G of biocrust-covered surfaces at the different developmental stages of semi-fixed and fixed dunes.

Sand dune	Biocrusts type	Fitted equation and related parameters $y = y0 + 2A/\pi \times (W/(4(X\text{-}Xc)^2 + W^2))$				R_{max}	T/Quadrat (20 × 20 cm)	G animal unit day/ha	Correlation coefficient R^2	P value
		y0	A	W	Xc					
Semi-fixed dune	CC	9.1	218.7	14.1	13.3	9.8	13.3	9.6	0.87	< 0.001
	LC	6.1	609.9	27.2	15.0	14.3	15	10.9	0.93	< 0.001
	MC	1.9	1219.7	44.4	19.9	17.5	19.9	14.4	0.53	< 0.001
Fixed dune	CC	8.6	342.1	20.3	15.3	10.7	15.3	11.1	0.80	< 0.001
	LC	5.5	754.3	33.4	15.6	14.4	15.6	11.3	0.95	< 0.001
	MC	2.7	1281.3	42.8	20.0	19.6	20.0	14.4	0.85	< 0.001

Note: CC, LC and MC represent cyanobacterial crust, algae-lichen mixed crust and moss crust, respectively. R_{max} represents the maximum surface roughness. T represents the trampling intensity corresponding to R_{max} in the quadrat. G represents the moderate grazing intensity calculated from formula 2 (animal unit day/ha).

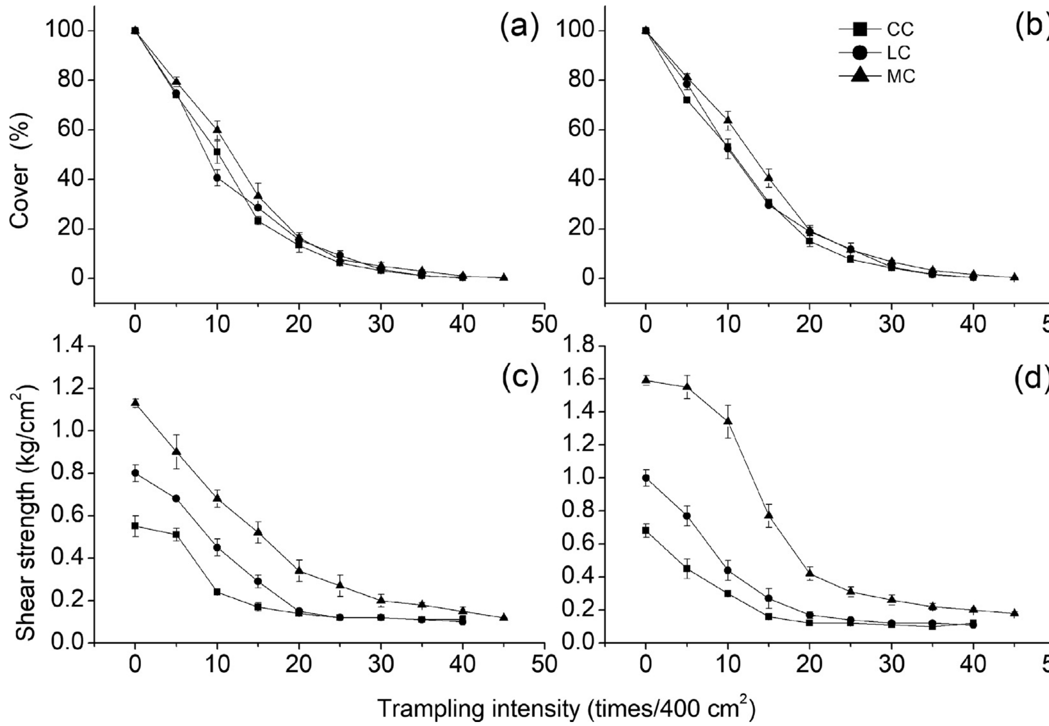

Fig. 4. Changes in coverage and shear strength of biocrust-covered soil of semi-fixed (a, c) and fixed (b, d) dunes at different stages of development with trampling intensity. CC, LC and MC represent cyanobacterial crust, algae-lichen mixed crust and moss crust, respectively.

strength of the MC-covered soil was always greater than that of the CC- and LC-covered soils. On the other hand, the reduction rates, coverage and shear strength of the CC and LC were greater than that of the MC (Fig. 4).

A significant linear relationship was observed between the variation of surface roughness (both increasing and decreasing) and the change in biocrust coverage as the trampling intensity increased at different developmental stages for the fixed and semi-fixed dunes (Fig. 5). In addition, a significant linear relationship was observed between the variation of surface roughness of the MC-covered soil and change in the surface shear strength (Fig. 6). The sensitivity of the surface roughness of the fixed dunes to variations in the biocrust coverage and surface shear strength was greater than that of the semi-fixed dunes (Figs. 5 and 6).

4. Discussion

4.1. Response of the surface roughness of biocrust-covered soil to trampling disturbance

The surface roughness of the biocrust-covered soil showed a single peak as the trampling intensity increased (Fig. 3). The increasing trampling intensity did not lead to a continuous decrease of surface roughness of the biocrust-covered sandy soil. The surface roughness of the biocrust-covered soil on both fixed and semi-fixed dunes at different development stages increased by 1.6 to 3 times (Fig. 3), although the coverage of biocrust decreased by more than 50% (Fig. 4(a, b)) compared to that before the trampling disturbance. In the Loess Hilly area in northern China, the surface roughness increased by 91% under 50% trampling disturbances (based on the coverage of the broken biocrust) compared to that without disturbances (Shi et al., 2017). In Jasper National Park of Canada, trampling by ungulates improved the surface micro-topography of moss-covered soil, although the moss coverage did not decrease substantially as the density of footprints increased until 25% of the surface was covered by footprints because disturbed moss crust remains attached to the soil surface (Csotonyi and Addicott, 2004). The increasing rate of surface roughness and the decreasing rate of biocrust coverage to trampling disturbance in our study were higher than that of the non-sandy area. These results indicated that the surface roughness of the biocrust-covered sandy soil is more sensitive to trampling disturbance than that of the non-sandy area. This study also found that the disappearance of the MC coverage from the surface of soil required more trampling repetitions than that of the CC and LC (Fig. 3), indicating that the MC was more resistance to trampling disturbance than CC and LC. Moreover, this finding implies that the response of surface roughness of biocrust-covered soil to trampling disturbance is not only dependent on the characteristics of subsurface soil under the biocrust but is also driven by the development stage of the biocrust (Belnap, 2006).

We also found that the surface roughness of the fixed dunes was higher than that of the semi-fixed dunes. However, the rate of increase for the surface roughness of the semi-fixed dunes covered by biocrust was higher than that of the fixed dunes as the trampling intensity increased (Fig. 3). This phenomenon may be explained by the following two aspects: first, the surface roughness of the semi-fixed dunes before disturbance is smaller than that of the fixed dunes, and the former may form a greater difference in surface roughness in the initial stage of trampling disturbance; and second, the thickness and content of fine particles of biocrust on the semi-fixed dunes are lower than that of the fixed dunes (Table 1). The thinner biocrust rich in sand would be expected to be more sensitive to disturbance than the thicker biocrust rich in silt and clay because of the structure of latter is more stable than that of the former (Kidron et al., 2010; Li et al., 2017), which results in a faster rate of increasing surface roughness of the semi fixed dune than the fixed dune. The rate of decreasing surface roughness of the fixed dunes covered by biocrust was lower than that of the semi-fixed dunes as the trampling intensity increased (Fig. 3), which might be related to a lower rate of decreasing biocrust coverage of the fixed dunes compared with that of the semi-fixed dunes when the trampling strength increased (Fig. 4(a, b)). These differences indicated that the response of surface roughness of biocrust-covered soil to trampling disturbance due to grazing varied with the degree of sand dune fixation. However, the

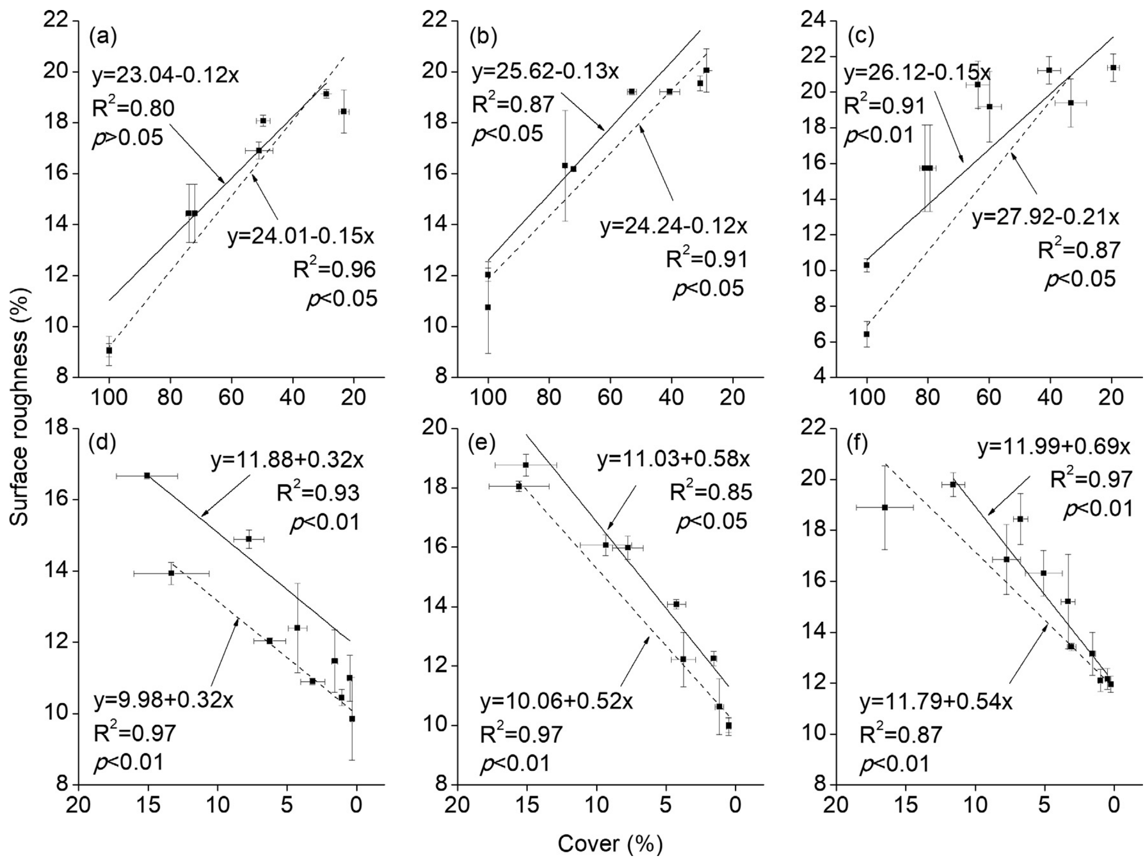

Fig. 5. Relationship between biocrust coverage and surface roughness. (a, b, and c represent the process of increasing roughness on the semi-fixed (dotted lines) and fixed dunes (solid lines) with CC, LC and MC biocrusts, respectively; d, e, and f represent the process of decreasing roughness on the semi-fixed (dotted lines) and fixed dunes (solid lines) with CC, LC and MC biocrusts, respectively. CC, LC and MC represent cyanobacterial crust, algae-lichen mixed crust and moss crust, respectively).

distribution pattern of biocrusts at different developmental stages on the surface of the fixed and semi-fixed dunes was quite different (Wu et al., 2012; Zhang et al., 2013). The surfaces of the fixed dunes were dominated by MC, while the surfaces of the semi-fixed dunes were mainly covered by CC and LC (Zhang et al., 2013). Hence, the distribution proportion of biocrust on the surfaces of the fixed and semi-fixed dunes should be considered to increase the surface roughness by trampling disturbance due to grazing.

4.2. Mechanism of the response of biocrust-covered soil roughness to trampling disturbance due to grazing

The difference in response of surface roughness of biocrust-covered soil at different developmental stages to trampling disturbance due to grazing can be interpreted as follow. First, the well-developed MC had higher shear strength. The structure of the MC is more difficult to be crushed than that of the CC and LC (Xie et al., 2007). Densely structured MC forms larger surface micro-fluctuations at the beginning of trampling, which probably increased the surface roughness of the MC-covered soil higher compared with the CC- and LC-covered soil (Fig. 6). As the trampling intensity increased, the dense structures of the MC were destroyed by trampling but the shear strength of surface covered by MC was always greater than that covered by CC and LC (Fig. 4(c, d)). Greater shear strength can form higher surface micro-reliefs during trampling (Duan et al., 2004), which slows down the process of surface roughness reduction, thereby leading to the greater surface roughness of the MC-covered soil than the CC- and LC-covered soil. Second, the thickness of the MC was greater than that of the CC and LC. Under tramping disturbance, larger biocrust remnants and blocks created by thicker MCs were more difficult to be buried by loose sand under the crust layer, which slowed down the disappearance of biocrust debris from the surface soil, whereas an opposite pattern was observed for the thinner CC and LC (Fig. 4(a, b)). Therefore, the variation of crust coverage and surface shear strength as the trampling intensity increased is an important internal mechanism for the different responses of biocrusts at different developmental stages under trampling disturbance by grazing.

The differences of surface roughness of the biocrust-covered soil on the fixed and semi-fixed dunes as the trampling intensity increased can be explained by differences in the development characteristics of biocrust. The development characteristics of biocrust on the surface of the fixed dunes were higher than those of the semi-fixed dunes (Table 1). In the process of increasing surface roughness, the well-developed biocrusts on the fixed dunes could form more significant topographic fluctuations than the less-developed biocrusts on the semi-fixed dunes, resulting in greater surface roughness of the fixed dunes compared with the semi-fixed dunes. Moreover, while the surface roughness continued to decline, well-developed biocrusts on the surface of the fixed dune disappeared more slowly from the surface compared with the less-developed biocrusts, thus resulting in the greater surface roughness of the fixed dunes than the semi-fixed dunes. This difference explains the greater sensitivity of the fixed dunes to variations of biocrust coverage and shear strength compared to the semi-fixed dunes (Figs. 5 and 6).

4.3. Implications for sandy land ecosystem management

The vital roles of biocrusts in ecosystems are widely recognized (Bowker, 2007; Kidron, 2019). Also, the negative effects of biocrusts on evaporation (Kidron and Tal, 2012) and soil moisture interception (Li et al., 2010; Qiu et al., 2015; Yang et al., 2015; Xiao and Hu, 2017) have

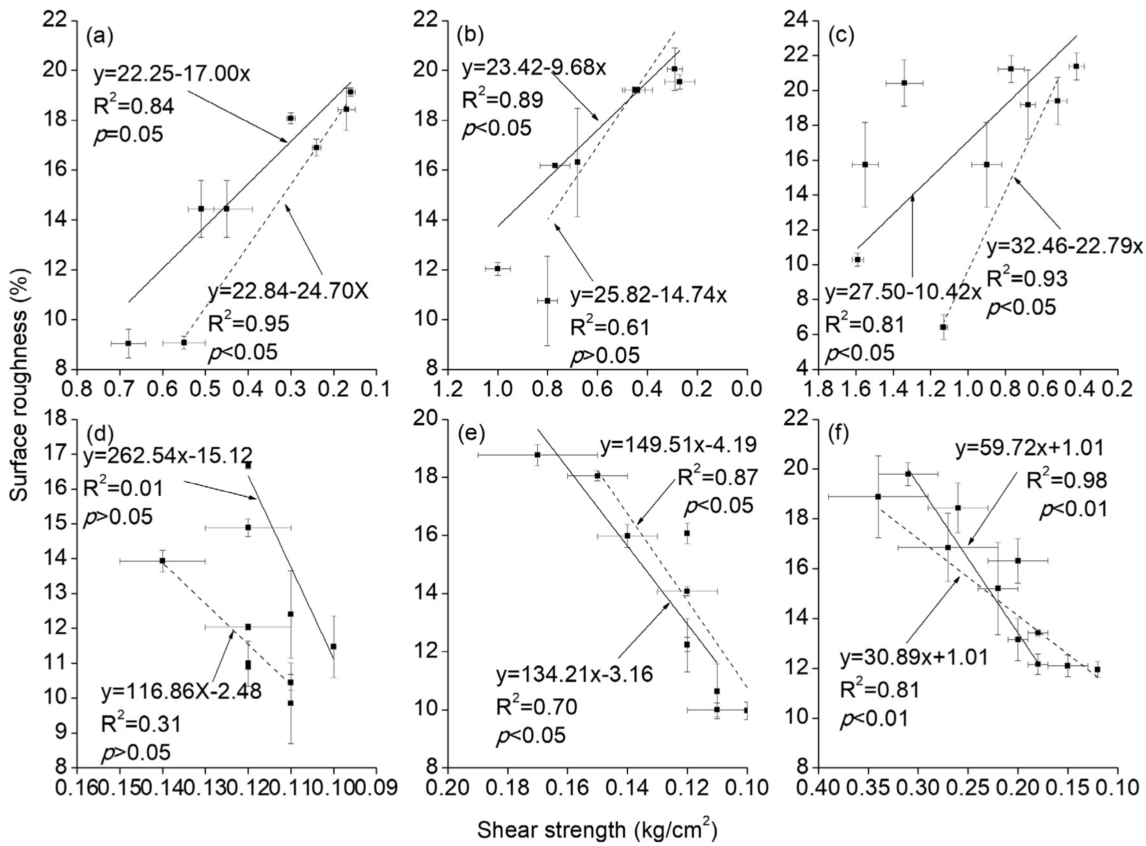

Fig. 6. Relationship between the surface shear strength of the biocrust-covered soil and surface roughness. (a, b, and c represent the process of increasing roughness on the semi-fixed (dotted lines) and fixed dunes (solid lines) with CC, LC and MC biocrusts, respectively; d, e, and f represent the process of decreasing roughness on the semi-fixed (dotted lines) and fixed dunes (solid lines) with CC, LC and MC biocrusts, respectively; CC, LC and MC represent cyanobacterial crust, algae-lichen mixed crust and moss crust, respectively).

received considerable attention. For the scientific management of sandy land ecosystems, reducing the negative effects of biocrusts on soil moisture and increasing the surface roughness by grazing and trampling disturbance are worthwhile research topics. Understanding the complex and non-linear relationships between variations of surface roughness and the associated ecological functions is an important prerequisite for the scientific management of biocrust-covered sandy ecosystems.

Our results showed that moderate grazing (grazing intensity less than *G*) was beneficial to increasing the surface roughness while severe trampling (grazing intensity higher than G) led to a decrease in the surface roughness (Fig. 3 and Table 2). Increases of surface roughness changed the ecological and hydrological functions of the biocrust-covered surface soil. First, increased surface roughness prolonged the duration time of rainwater on the soil surface, increased the in situ infiltration of soil water and availability of deep soil water, and alleviated drought stress to deep-rooted sand-fixed shrubs due to the water interception effects of biocrust (Kidron et al., 2012; Rodriguez-Caballero et al., 2018; Yair et al., 2011; Xiao and Hu, 2017). Second, increased surface roughness was beneficial to the lodgement possibility of plant seeds on the soil surface, facilitated the process of vascular plant settlement on the disturbed surface, and affected the plant settlement and species composition of the associated areas (Prasse and Bornkamm, 2000). Third, increased surface roughness changed the micro-environment of surface soil, slowed down the evaporation processes of soil moisture, prolonged the wetness duration time of soil moisture and photosynthetic activity of biocrust-covered surface soil, mediated the carbon exchange process of the surface soil, and then affected the regional soil carbon balance. In addition, improvements in the micro-environment induced by surface roughness had a positive impact on the growth of mosses and dynamics of microbial activity (Csotonyi and Addicott, 2004; Bao et al., 2019) and then affected the biogeochemical processes of surface soil. Fourth, increased surface roughness was conducive to the accumulation of fine particles in the soil surface and promoted the formation process of desert soil (Williams et al., 2012).

Although moderate grazing increased the surface roughness of biocrust-covered soil, it inevitably reduced the coverage of biocrust on the soil surface (Figs. 3 and 4), thus affecting many ecological and hydrological processes of desert ecosystems. First, the decreased biocrust coverage increased the exposed area of the surface, reduced the runoff amount or the possibility of runoff generation, changed the initial redistribution processes of resources, such as water, sediments, nutrients and seeds, between shrub patches and crust patches in arid dune ecosystems, and then affected the resource exchange, vegetation coverage, productivity and distribution pattern (Wilcox and Allen, 2003; Li et al., 2008; Yair et al., 2011; Kidron, 2016). Simultaneously, the decreased coverage also increased the in situ infiltration of soil moisture and availability of deep soil water (Golodets and Boeken, 2006), and decreased the resource redistribution processes such as runoff, related sediments and nutrients (Kidron, 2016). When the trampling disturbance was relieved, the fine-textured surface sealed again under the rainfall events (Chamizo et al., 2012) or developed into the early stage of biocrust, and the role of the biocrust in water and related resources redistribution was partially or completely recovered (Kidron, 2015; 2016; Xiao et al., 2015). Second, the decreased biocrust cover led to a loss of protection by the crusts, thereby increasing the possibility of surface erosion (Zhang et al., 2006; Chamizo et al., 2017). Decreased biocrust cover also increases the possibility of plant seed burial by sand, which facilitates the possible lodgement of vascular plants on the surface, thus affecting the establishment and species composition of vascular plants (Kidron et al., 2010; Briggs and Morgan, 2011), which has a positive feedback on the formation and development of biocrusts on the soil surface (Prasse and Bornkamm, 2000). Third, the decreased biocrust coverage slowed down the evaporation process of soil moisture from soil surface and prolonged the wetness duration time of soil moisture in the surface soil (Kidron and Tal, 2012).

Moderate grazing also decreased the shear strength of the biocrust-covered soil, which in turn affects ecological and hydrological function of soil surface. On the one hand, the reduction of the shear strength induced by moderate grazing softened the surface soil, increasing the possibility of vascular plant seeds penetrating into the mineral soil or subsurface sediments, which is conducive to the settlement process of vascular plants on the surface (Prasse and Bornkamm, 2000; Kidron et al., 2010; Briggs and Morgan, 2011). On the other hand, moderate grazing destroyed the compacted structure of the biocrust-covered soil, decreased the shear strength of the surface soil, increased the in situ infiltration of rainfall, reduced the amount of runoff and then affected the process of resource redistribution and vegetation distribution pattern in arid dune ecosystems (Yair et al., 2011; Faist et al., 2017).

Moderate trampling not only increased the surface roughness but also decreased the biocrust cover and shear strength of surface soil, thereby affecting the ecological and hydrological functions of the biocrust-covered surface. Such effects may include a trade-off between the positive and negative effects of increased surface roughness on many of the ecological and hydrological processes of desert ecosystems mentioned above. To minimize the negative impact of trampling on the functions of biocrust-covered soil, the proper time for trampling disturbance is at the end of the monsoon season and the beginning of the rainy season. At those times, the negative impacts of trampling on the ecological and hydrological functions of biocrust-covered soil will be the lowest, the disturbed biocrust can recover well after a rainy season, and the ecological and hydrological functions of the biocrust can be recovered partially or completely (Kidron, 2015; Xiao et al., 2019). Biocrusts can be protected even with a disturbance with these measures, and the best balance can be achieved. It should be noted that the natural recovery rate of biocrusts is limited by precipitation (Xiao et al., 2015), and large fluctuations in rainfall amounts occur between wet years and dry years in the study area (Wu et al., 2012). Therefore, when implementing moderate grazing, the interannual difference of regional precipitation in addition to the trampling time should be considered. Compared with moderate trampling due to grazing, severe trampling (grazing intensity higher than *G*) leads to a significant reduction in both the surface roughness and coverage of biocrust (Figs. 3 and 4(a, b)), thereby leading to significant structural and functional changes of the surface soil (Maestre et al., 2016). This study provides an important scientific basis for the grazing management of the Mu Us Sandy Land and similar ecosystems to determine the appropriate degree of mechanical disturbance on biocrust-covered surfaces.

Grazing is often considered to cause ecosystem degradation or desertification in vulnerable ecosystems. In this study, well-timed moderate grazing disturbance was used as a management tool to increase the surface roughness of biocrust-covered soil and reduce the negative impacts of biocrusts in sandy land ecosystems. Thus, the positive and negative impacts of the increased surface roughness caused by moderate grazing on ecosystem functions can be balanced through the scientific management of sandy ecosystems. The novelty of this study was determining the threshold range for the scientific management of sandy land ecosystem covered with biocrusts by mimicking sheep trampling disturbance. However, the responses of biocrust-covered sandy surfaces to trampling disturbance under wet conditions need to be further studied to obtain more information about surface roughness and adopt more precise management measures.

5. Conclusions

We concluded that moderate sheep grazing (grazing intensity less than *G*) was beneficial to increasing the surface roughness while severe grazing (grazing intensity higher than *G*) decreased both the surface roughness and coverage of biocrust, thereby leading to significant changes in the surface soil structure and functions. Increased surface roughness positively and negatively affects many ecological and hydrological processes of sandy land ecosystems. To increase the surface roughness and minimize the negative impacts of trampling disturbance on biocrust-covered soil, the degrees of dune fixation, biocrust development, trampling time and interannual precipitation variability should be carefully considered. This study provides an important scientific basis for the grazing management of the Mu Us Sandy Land and similar ecosystems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2019.114146.

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