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Freeze-thaw cycles aggravated the negative effects of moss-biocrusts on hydraulic conductivity in sandy land

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ABSTRACT

Moss-biocrusts (BCs) play an essential role in soil stabilization, but it reduces soil hydraulic conductivity, hindering precipitation convert to soil water. Freeze-thaw cycles (FTCs) is a natural phenomenon, which can alter soil properties, causing widespread concern. However, few studies have focused on the effects of FTCs on hydraulic conductivity in BCs, which may alter the negative effects of BCs on hydraulic conductivity. We conducted an *in-situ* FTCs simulated experiment in BCs and bare sand (BS), to analyze the response of particle-size composition, water-stable aggregates and water repellency (WR) to FTCs, and their effects on saturated hydraulic conductivity (K_s). The results showed that the existence of BCs had affected water-stable aggregates, particle-size composition, WR and K_s. Compared with BS, the percentage of clay-size particle content increased by 44% and 60% in BCs layer and its underlying soil, respectively. The stability of water-stable aggregates was 19% higher in BCs than the measured stability in BS. K_s of BS was 2.4 times higher than that of BCs, and the increasing percentage of water-stable aggregates larger than 5 mm would reduce K_s in sandy land. FTCs had the significant effects on water-stable aggregates, WR and K_s. WR and K_s of BCs were decreased 57% and 25% after FTCs, respectively. Moreover, after FTCs, the percentage of soil water-stable aggregates $>$ 5 mm reduced 19%, while 1–5 mm increased 18%. WR and sand content were significantly and negatively correlated with K_s, while clay content and the percentage of soil water-stable aggregates $>$ 5 mm were significantly and positively correlated with K_s in BCs. Our results indicated that BCs and FTCs had a significant and negative effects on K_s. FTCs further decreased the hydraulic conductivity, which was not conductive to the supply of meltwater to soil water reservoir in the period of winter and early spring.

1. Introduction

Climate change is inducing warming conditions at mid-high or high altitude, especially in winter, leading to the increase of air and soil temperature (Mellander et al., 2007; Kurylyk et al., 2014). With temperature increasing, seasonal frozen soil generally thaws at day, and freezes at night when temperature decreases (Alamusa et al., 2014). It is expected that the phenomenon of freeze-thaw cycles (FTCs) in winter and early spring will be more frequent in the coming years (Sahin et al., 2008; Ozgul et al., 2011). Freeze-thaw induces the transformation of soil water between solid state and liquid state, changing soil characteristics. However, the effects of FTCs on soil characteristics may positively or negatively (Sahin et al., 2008). A great number of studies have evaluated the response of soil structure and properties to FTCs (Oztas and Fayetorbay, 2003; Li and Fan, 2014; Wang et al., 2015; Xiao et al., 2019c), and have proved that FTCs can alter soil particle-size composition and the stability of aggregates (Oztas and Fayetorbay, 2003; Xiao et al., 2020), favoring higher soil erodibility (López-Vicente et al., 2008). With

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an increasing frequency of FTCs, Li and Fan (2014) observed that macro-size groups of water-stable aggregates decreased, while the proportion of micro-size groups increased. Hanay et al. (2003) have indicated that aggregate stability and hydraulic conductivity of saline-sodic soils decreased with the increasing FTCs. Long-term freeze-thaw processes change soil particle-size composition, and that influences soil structure (Zhang et al., 2016).

Biocrusts (BCs) are mainly composed of mosses, lichens, algae, fungi and bacteria, and the ground coverage area can reach up to 40–100% in open dry-climate areas (Elbert et al., 2012; Xiao et al., 2016). BCs are usually distributed in the 0–2 cm soil depth and is regarded as a significant component of arid and semiarid ecosystems. Biocrusts are considered as ecosystem engineers in drylands, and play an important role in soil stabilization, preventing soil erosion by changing soil surface structure and inner properties (Zhao and Xu, 2013; Gao et al., 2017; Moreno-Jimenez et al., 2020). However, some studies have revealed that BCs cause a decrease in soil infiltrability and an increase of surface evaporation (Kidron and Tal, 2012; Xiao and Hu, 2017; Cui et al., 2021), and both processes have a negative effect on soil water replenishment and balance. Moreover, the decrease of infiltrability induces the increase of soil surface evaporation and reduces soil available water, which is not conductive to the establishment of vegetation in drylands. The study of BCs is of great concern in the recent years, as they have significant effects on soil water balance and germination (Chamizo et al., 2016; Ferrenberg et al., 2018; Cui et al., 2021). Kidron and Tal (2012) demonstrated that BCs decrease soil water content and increase evaporation rate compared with the status of soils without BCs. Otherwise, the soil organic matter content of soils with BCs can be up to four times higher than that of the non-crusts soils, and the presence of BCs increases the proportion of fine particles (Gao et al., 2017). Generally, the existence of BCs changes soil properties and exerts an intense influence on hydrological processes in drylands.

Soil saturated hydraulic conductivity (K_s) is an important factor to quantify soil infiltration capacity, and it is significantly influenced by soil properties (Fodor et al., 2011). Thick BCs with dense surface structure can retain more precipitation and swell by absorbing water, blocking the ground surface porosity and decreasing water content of the soil layer underlying BCs (Kidron and Tal, 2012; Li et al., 2018; Xu et al., 2020; Cui et al., 2021). BCs increases the content of hydrophobic substances (such as organisms), and the swelling of exopolysaccharides would block soil pores, these processes ultimately reducing the hydraulic conductivity (Fischer et al., 2010). In addition, some physical properties of soils underlying BCs significantly influence K_s, such as the particle-size composition and aggregate stability (Xiao et al., 2019a,b,c). Rossi et al. (2012) reported that the content of clay- and silt-size particles were negatively correlated with K_s, whereas the correlation with the content of sand-size particles was positive. Generally, FTCs may affect K_s by influencing biocrusts characteristics and changing soil properties (Xiao et al., 2016; Xiao et al., 2019a,b,c). Wang et al. (2015) indicated that FTCs would detriment BCs and increase K_s.

BCs are widely distributed in soil surface and influence hydrologic processes due to its special structural features (Ferrenberg et al., 2015; Wang et al., 2015). The supply of meltwater to soil water in the period of winter and early spring is an important process to improve soil water content, favoring plants growth and survival rate. FTCs may alter hydraulic conductivity of BCs and further influence the amount of meltwater supplied to soil water. As a key parameter of hydraulic conductivity, K_s plays an important role in evaluating soil infiltrability. However, the role that FTCs play in altering K_s of BCs is generally ignored. In this study, we hypothesize that FTCs could improve K_s by breaking water repellency weakening the negative effects of BCs on soil permeability. To test this hypothesis, we conducted an *in-situ* FTCs simulation experiment in a semi-arid sandy land of China where moss-biocrusts are widely spread. In particular, we have investigated the effects of FTCs on K_s, including a non-crust covered soil (bare sand) as control. The variation of water repellency, bulk density, particle-size composition, water-stable aggregates and K_s were measured in surface soil layers. This study aims to quantify the effects of BCs and FTCs on soil properties in order to reveal the influencing of BCs on K_s in future.

2. Materials and methods

2.1. Study area

The study was conducted in the southern part of the Mu Us sandy land (38°46′ N, 110°21′ E, 1222 m a.s.l.) on the northern Loess Plateau in China (Fig. 1a). It belongs to a typical continental semiarid monsoonal climate region. The average annual precipitation is about 409 mm (80% concentrated in summer), and the average annual potential evapotranspiration is 1337 mm. The mean annual temperature is 8.4 °C (Xiao et al., 2016). Winter last for 110 days from November 21st to March 10th. January is the coldest month and the average temperature is −9.9 °C. The mean lowest and highest daily air temperature was −12.5 °C and 1.8 °C during the experiment. Due to the large temperature difference between day and night in winter of northwestern China, soil freezing at night and thawing at day is a common natural phenomenon. In northern China, the “Grain-for-Green” program has been implemented in recent decades, allowing vegetation recovery and favoring the arising of biocrusts (Fig. 1b), which are currently extensive on fallow lands, shrublands and grasslands, with a ground coverage that has reached up to 70–80% (Xiao et al., 2010). Spring is the period of vigorous growth of mosses, and it was generally dormant and become yellow in winter.

2.2. Experimental design

The experiment was conducted on January 9th – 26th, 2021, in a moss-biocrusts covered sandy land and bare sand (without biocrusts) as control. Three 10 × 10 m sites were selected in biocrusts and bare soil, and the distance between each site was > 500 m to minimize the risk of sampling in non-independent sites. The soil on the experiment site is an aeolian sandy soil and in the phase of frozen. During experiment period, the soil thawing depth was generally at 0–5 cm soil layer under natural condition.

At each experimental site, the snow melting experiment was done in three plots with and without biocrusts. A heating equipment (NSB-19), located at 60 cm height above the ground, was used to increase the air temperature (Fig. 2). The melting experiment was conducted from 9:00 AM to 12:00 PM, and before starting the experiment, the thickness of snow was ca. 4 cm on the soil surface of both the bare sand and the soils with biocrusts. The variation of soil temperature and water content was monitored by using 5 sensors (METER/Decagon in USA) and EM50 data collector in 0–2 cm (biocrust layer) and 2–5 cm (soil underlying biocrust) soil layers.

For the freeze-thaw cycles (FTCs) experiment, the similar plots with the melting experiment were selected, and the snow cover was set before heating at 4 cm thickness; then, the continuous heating time was 3 h from 13:00 PM to 16:00 PM. The experimental plots were frozen at night naturally. The complete freeze–thaw process was repeated for 6 cycles. In bare sand and biocrusts without FTCs nearby (no more than 1 m) the FTCs treatment was regarded as control (Fig. 2).

The variation rates of soil temperature and water were used to evaluated their change rate within a certain time, and calculated as the following equation:

$$RT = \frac{T_i - T_0}{t} \tag{1}$$

$$RW = \frac{W_i - W_0}{t} \tag{2}$$

where RT is variation rate of soil temperature (°C min^{-1}); Ti is the temperature at *ith* min (°C); T_0 is the initial temperature within a certain

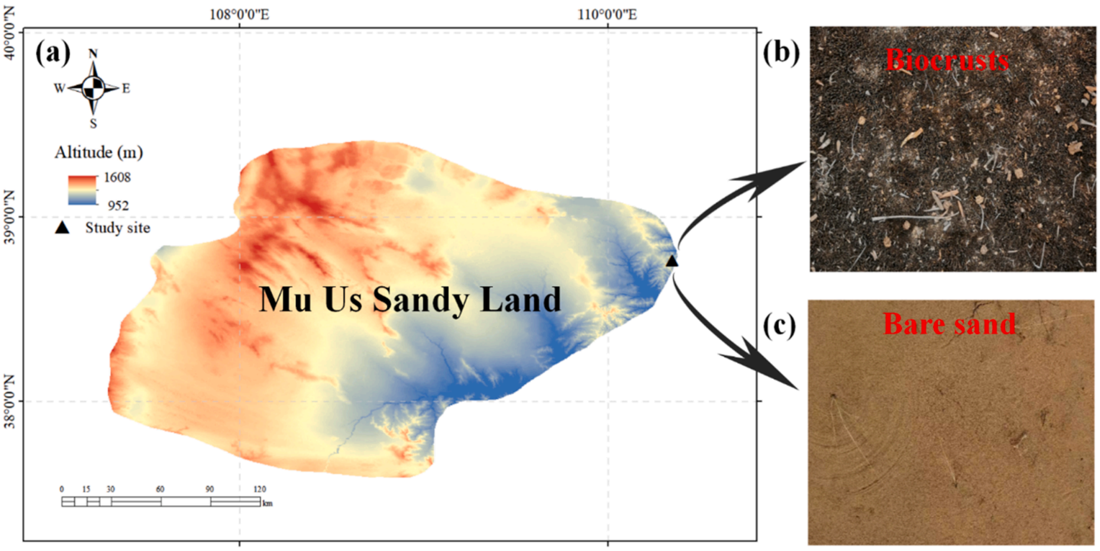

Fig. 1. Location of the study area (Mu Us Sandy Land, a), sampling site of biocrusts (b) and bare sand (c).

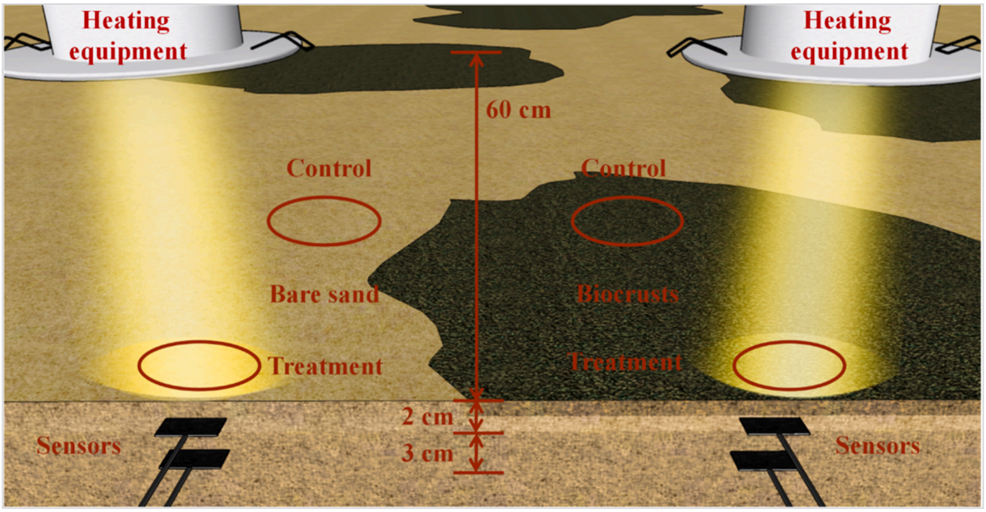

Fig. 2. Relative position schematic of each treatment and experimental design. Heating equipment was used to simulate warming, and the distance from ground surface was 60 cm. The shape of dark green represented the moss-biocrusts, and shape of yellow represented the bare sand. The heating area as the treatments, and the unheated adjacent area as the control. Sensors were inserted into 0–2 cm and 2–5 cm soil layer in bare sand and biocrusts to monitor the variation of soil water and temperature during the heating process. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

time (°C); t is time that temperature changed from T_0 to T_i; Rw is variation rate of soil water content (% min^{-1}); W_i is the soil water content at *ith* min (%); W_0 is the initial soil water content within a certain time (%); t is time that soil water content changed from W_0 to W_i.

2.3. Measurements of biocrust characteristics and soil properties

At each biocrust cover plot, the biocrust was collected by using a cutting ring (2 cm height, 6.18 cm diameter) to measure biocrust water repellency at the laboratory. The top 0–5 cm soil was taken by using 5 cm height and 5.046 cm diameter cutting rings to measure saturated hydraulic conductivity (K_s) and bulk density (BD), with two repetitions in each plot. Meanwhile, using an aluminum box undisturbed soil in 0–5 cm depth was collected, distinguishing 0–2 cm and 2–5 cm depth soil to measure soil water-stable aggregates and particle-size composition.

In the laboratory, soil water repellency was measured by the water drop penetration time (WDPT) method (Letey et al., 2000). Soil samples in the cutting ring were oven-dried at 105 °C until constant weight to calculate soil bulk density (BD, g·cm^{-3}). The soil particle-size distribution was determined through a laser particle-size analyzer (Mastersizer 2000, Malvern Instruments Ltd., UK). According to the international classification standard of soil particles, soil particles are divided into three grades including clay (<0.002 mm), silt (0.002 ~ 0.05 mm) and sand (>0.05 mm). Soil in aluminum containers was used for measuring soil water-stable aggregates by the wet sieving method (Kakeh et al., 2018). The soil mean weight diameter (MWD, mm) was calculated using the following equation (Parent et al., 2012):

$$MWD = \sum_{i=1}^{n} \overline{X_i} W_i \tag{3}$$

where $\overline{X_i}$ (mm) is the assumed diameter for the ith fraction, W_i is the weight fraction remained on the ith sieve-size, and n is the number of sieves.

On each site, a plot covered with intact moss-biocrust was selected to measure the infiltration rate by using a double-ring infiltrometer. The double-ring consisted of an external ring (11.5 cm height, 35.5 cm diameter,) and an internal ring (11.5 cm height, 20 cm diameter). The water was added in the inner and outer ring up to 5 cm height. And record the time when the water level dropped 1 cm and then added water to keep the water level at 5 cm height. The measurement will quit when the infiltration time was very nearly the same three consecutive measurements. Bare sand nearby was regarded as control, and three repetitions were taken on each site. The specific method was referenced from Guo et al. (2019).

Soil saturated hydraulic conductivity was measured by using indoor-ring infiltration method. Undisturbed soil samples were taken by using cutting ring (5 cm height and 5.046 cm diameter), then taken back to the laboratory and soaked for 8 h. Put a same sized and empty cutting ring on soaked soil samples, the interface was sealed with a leather sleeve to prevent water leakage and put into a funnel. Added water to the upper empty ring and the water level as high as the ring edge. Adjusted a Mariotte bottle to ensure that the water head unchanged. Then put an empty bottle under funnel to catch the drips and weighted the collected water every 10 min, until the amount of water seepage is equal in unit time, the experiment lasted approximately 3 h. When the measurement was quit, using the vernier caliper to measure the distance of water level to the upper edge of ring to calculate the water head. The soil saturated hydraulic conductivity (K_s, mm·min^{-1}) was calculated as the following equation:

$$Ks = \frac{10 \times Q_n \times L}{t_n \times S \times (h + L)} \tag{4}$$

where Q_n is the seepage water weight for the n^{th} weighed, t_n (s) is the interval time of each weighing, n is the number of Weighing times, h (cm) is the water head, L (cm) is the thickness of the soil layer. In order to convenience of comparison, the saturated hydraulic conductivity at T (°C) is converted to that at 10 °C; the calculation is as follows:

$$K_{10} = \frac{K_T}{0.7 + 0.03T} \tag{5}$$

where K_T (mm·min^{-1}) is the saturated hydraulic conductivity at T (°C), and T (°C) is the actual temperature at the time of measurement.

2.4. Data analysis

The significant differences of soil properties before and after FTCs in bare sand and biocrusts were statistically evaluated using the student's t test at 0.05 level. Two-way analysis of variance was used to assess the effects of surface soil type (biocrusts and bare sand) and treatment (before and after FTCs) on soil characteristics. Pearson coefficient was used for calculating the linear relationship between K_s and soil properties. The experimental data were analyzed and mapping by using IBM SPSS Statistics 22 and R 4.0.4 software.

3. Results

3.1. The variation of temperature and water content during thawing process

The initial temperature of bare sand (BS) was higher than that of BCs; it increased up to 13.4 °C in BS and 11.1 °C in BCs after 180 min (Fig. 3a). Soil temperature variation rates of BS were lower than the variation rates observed in BCs and soils underlying BCs. Temperature increasing rate decreased after 80 min in BCs, while it was 58% higher in BCs than that in BS (Fig. 3b). Soil water content dramatically increased after 20 min and trended to be stable after 80 min, and it was about 21% higher in BCs than in BS in 80–180 min (Fig. 4a). The soil water content increasing rate of BS was approximately 1.1 times higher than that of BCs after 100 min in the subsurface layer (Fig. 4c).

3.2. Effects of BCs cover and FTCs on sandy soil properties

The presence of BCs significantly increased the percentage of clay- and silt-size particles, and decreased the percentage of sand-size particles ($p < 0.05$; Fig. 5). Compared with BS, the percentage of clay in BCs, and its subsurface layer, increased by 44% and 60%, respectively. The percentage of silt in BCs, and its subsurface layer, was 3.7 and 2.6 times higher, and the percentage of sand was 13% and 14% lower than that of BS. After FTCs, the percentage of clay and sand were 9% and 12% lower in BCs compared to BS, while the percentage of silt was 4.8 times higher than that of BS.

The percentage of soil water-stable aggregates > 5 and 1–5 mm in

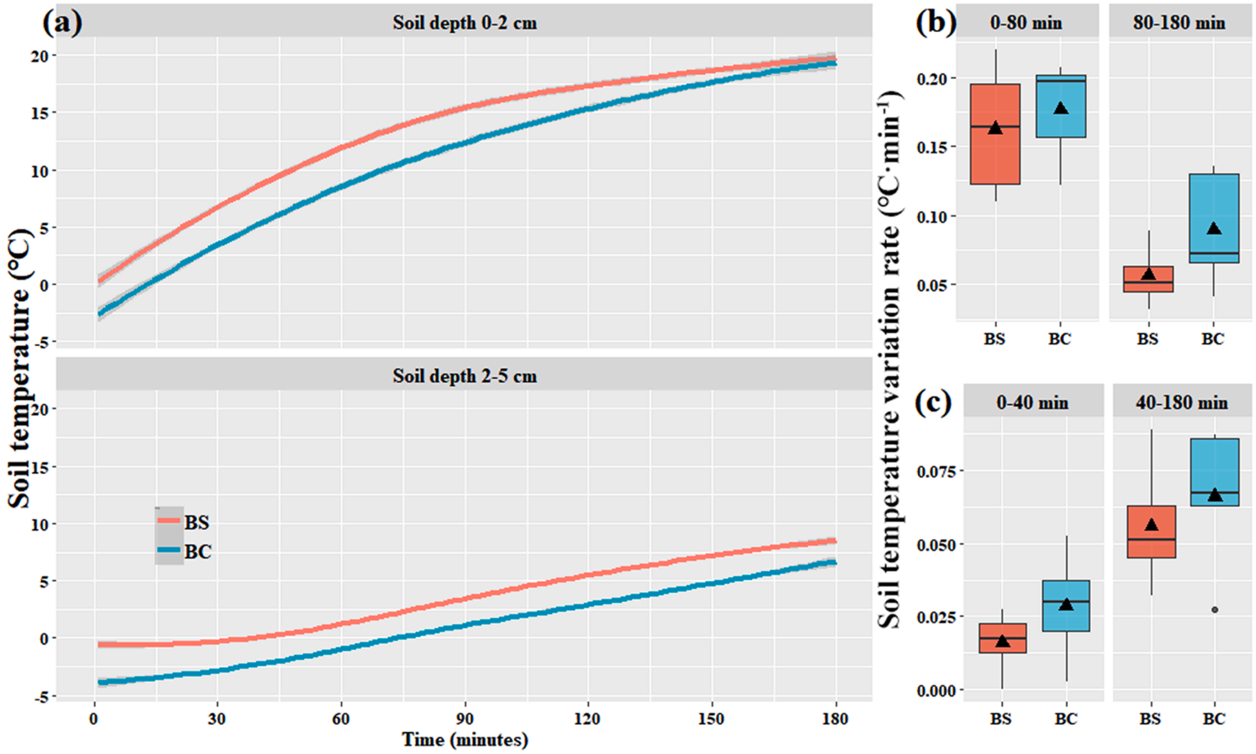

Fig. 3. (a) Soil temperature variation of bare sand (BS) and biocrusts (BC) in 0–180 min at 0–2 and 2–5 cm depth. Soil temperature variation rate at (b) 0–2 cm depth and (c) 2–5 cm depth. The black triangle is the mean value in each time period.

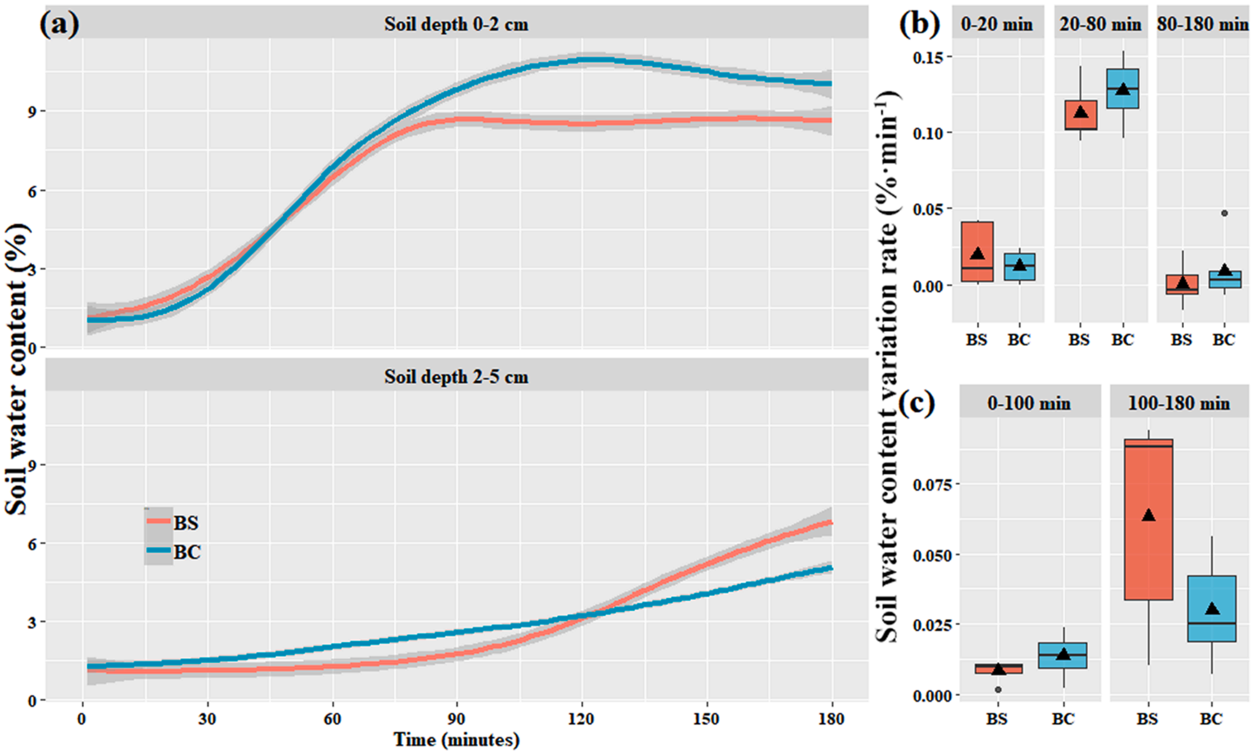

Fig. 4. (a) Variation of soil water content of bare sand (BS) and biocrusts (BC) in 0–180 min at 0–2 and 2–5 cm depth. Soil water content variation rate at (b) 0–2 cm depth and (c) 2–5 cm depth. The black triangle is the mean value in each time period.

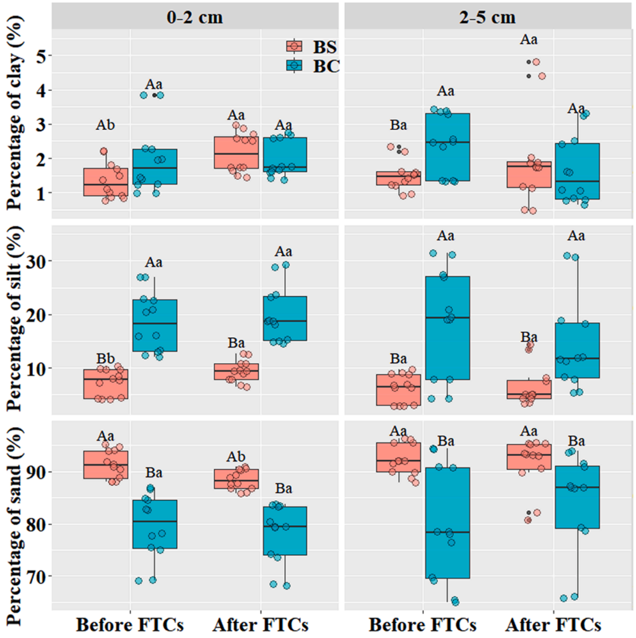

Fig. 5. The soil particle-size composition (clay, silt and sand) of biocrusts (BC) and bare sand (BS) before and after freeze–thaw cycles (FTCs) in 0–2 and 2–5 cm depth. The black triangle describes mean value under each treatment. The different capital letters indicate the difference of soil particles in the same treatment between biocrust and bare sand was significant ($p < 0.05$). The different lowercase letters indicate the difference of soil particles were significant between different treatment in the same sample site ($p < 0.05$).

Table 1
Changes in the soil bulk density (BD) and water-stable aggregates before and after freeze-thaw cycles in biocrusts and bare sand (mean ± SD).

Freeze-thaw cycles	Soil cover	BD	$D_{>5}$ (%)	$D_{1\text{-}5}$ (%)	MWD (mm)
Before FTCs	Biocrusts	1.27 ± 0.11Ba	49.77 ± 6.77 Aa	11.98 ± 2.11 Aa	2.98 ± 0.30 Aa
	Bare sand	1.44 ± 0.13Aa	2.98 ± 2.37 Ba	5.49 ± 0.76 Bb	0.63 ± 0.15 Bb
After FTCs	Biocrusts	1.31 ± 0.07 Ba	40.51 ± 3.16 Ab	14.17 ± 2.78 Aa	2.64 ± 0.17 Ab
	Bare sand	1.49 ± 0.08 Aa	7.45 ± 5.37 Ba	7.82 ± 1.94 Ba	0.92 ± 0.28 Ba

Note: $D_{>5}$, $D_{1\text{-}5}$: proportion of soil water-stable aggregates of > 5 mm and 1–5 mm particle size; MWD: mean weight diameter. The different capital letters indicate the difference of BD and water-stable aggregates in the same treatment between biocrust and bare sand was significant ($p < 0.05$). The different lowercase letters indicate the difference of BD and water-stable aggregates were significant between different treatment in the same sample site ($p < 0.05$).

BCs were approximately more than 15 times higher compared to BS. While they were about 7 times higher in BCs than that of BS after FTCs (Table 1). Moreover, the MWD was about 19 and 10 times higher in BCs than that of BS before and after FTCs, respectively. BD was 18% lower in BCs and 12% lower after FTCs compared to that of BS.

After FTCs, soil water repellency significantly decreased 57%, from strong water repellency to slight water repellency ($p < 0.05$; Fig. 6). On average, K_s of BCs was significantly lower than that of BS ($p < 0.05$; Fig. 7). Before FTCs, K_s was approximately 66% lower in BCs compared to BS, while it became 53% after FTCs. The decrease of K_s was 27% and 48% in BCs and BS after FTCs, respectively.

3.3. *Relationship between soil properties and K_s*

The results showed that soil surface tape (BCs and BS) had significant effects on water-stable aggregates, particle-size composition, K_s, BD and WR, while *FTCs* only had the significant effects on the percentage of soil water-stable aggregates 1–5 mm, clay content, K_s and WR ($P < 0.05$,

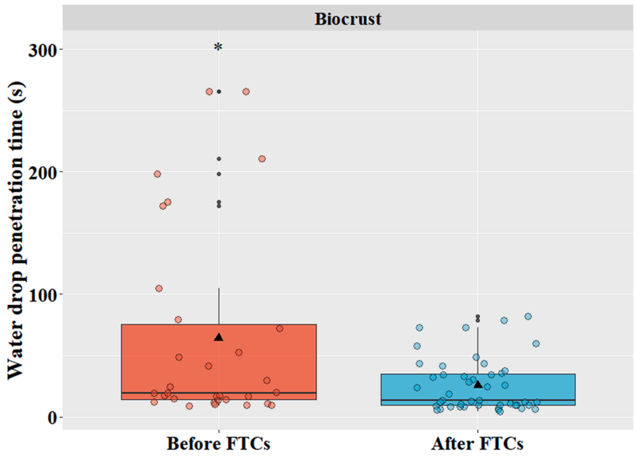

Fig. 6. Changes of biocrusts water repellency before and after freeze–thaw cycles (FTCs). The black triangle indicates mean value. * indicate the difference of biocrusts water repellency is significant before and after freeze–thaw cycles ($p < 0.05$).

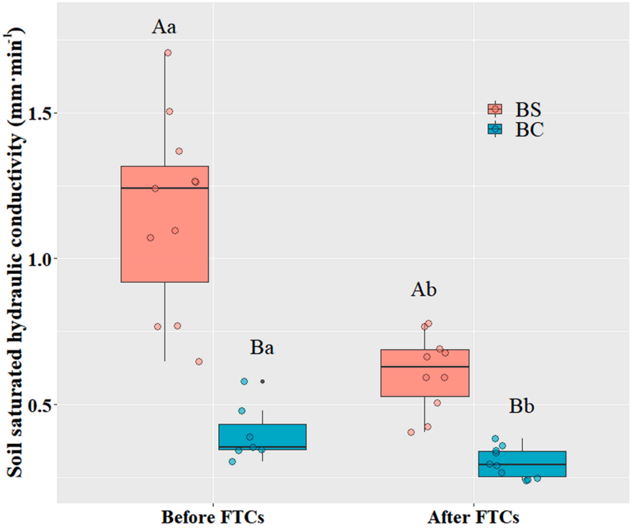

Fig. 7. Changes of soil saturated hydraulic conductivity of biocrusts (BC) and bare sand (BS) before and after freeze–thaw cycles (FTCs). The black triangle indicates mean value of each treatment. The different capital letters indicate the difference of saturated hydraulic conductivity in the same treatment (before or after FTCs) between biocrust and bare sand was significant ($p < 0.05$). The different lowercase letters indicate the difference of saturated hydraulic conductivity were significant between different treatment in the same soil surface types (bare sand or biocrust) ($p < 0.05$).

Table 2). The interaction effects of soil surface tape and *FTCs* treatment was significant on soil water-stable aggregates, clay content, K_s and WR.

K_s of BCs was significantly and negatively correlated with those of WR and sand content ($p < 0.01$; Table 3). While it was significantly and positively correlated with clay content. Conversely, K_s was positively correlated with sand content in bare sand. Moreover, the relationship of macro water-stable aggregates (particle size > 5 mm and 1–5 mm), MWD and K_s was not significant in sandy land ($p < 0.01$; Table 3).

4. Discussion

BCs play an important role in reducing soil erosion (Gao et al., 2017). However, the existence of biocrusts reduces soil hydraulic conductivity, and the low hydraulic conductivity is not conductive to the rainfall replenishment of soil (Cui et al., 2021). Due to the loose structure, sandy soil with the higher infiltrability. This study has proven that the initial infiltration rate and steady infiltration rate of BCs was 36% and 43% lower than that of BS, respectively (Table 4). Furthermore, through monitoring the variation of soil water content and temperature variation in snow melting process, we found that the temperature and initial water content were lower in BCs than in BS. The temperature increasing rates of BCs were generally higher than those of BS. The water content of BCs was higher than that of BS in the ground surface, while the water content and increasing rate of BCs were 53% lower than that of BS after thawing 100 min in the subsurface layer. These results indicated that BCs are sensitive to temperature variation and could hinder water infiltration by holding water in its structure. Many studies have reported that BCs are sensitive to climate change (Ferrenberg et al., 2018), and this process may be explained due to the variation of thermal properties (heat capacity, thermal conductivity and thermal diffusivity) of BCs in winter (Xiao et al., 2019a). Furthermore, biocrusts could maintain water in surface soil layer and restrain water infiltration, and that may result in the increase of evaporation in sandy land. Kidron and Tal (2012) also indicated that the evaporation was higher and water content was lower in biocrusts than bare soil.

The presence of BCs had the significant effects on water-stable aggregates, silt content, sand content, BD, WR and K_s of its underlying soil. The results indicated that compared to BS, biocrusts increases the proportion of clay and silt, meanwhile, the proportion of sand was reduced in its underlying soil (Gao et al., 2017; Wu et al., 2020; Cui et al., 2021). K_s of BCs was significant and negative related to the percentage of water-stable aggregates of 1–5 mm particle size, WR, sand content and BD. Available studies have showed that macro water-stable aggregates generally have strong WR, so that the increased percentage may result in the decrease of K_s in BCs. Moreover, the enhances of aggregate stability generally related to hydrophobic substances (Piyaruwan and Leelamanie, 2020), so that aggregate performs a certain strength on WR, which further decreases K_s. In addition, BCs could capture dust, resulting in the increase of fine particles in the surface layer (Reynolds et al., 2001), which may clog soil pore and further lead to the decreasing of K_s. Fischer et al. (2010) have also indicated that the physical density and the swelling of exopolysaccharides of biocrust would clogging soil pore, which decrease water infiltration. BD generally negative related to soil porosity, well structure soil with good pore connection which was conductive to the exchange of water and vapor. While the compact soil with higher BD limited the move of water flow.

Freeze-thaw event is a natural phenomenon and occurs frequently in drylands. Many reports have suggested that warming and increased precipitation frequency can induce the reduction of moss-biocrusts cover (Maestre et al., 2013; Ferrenberg et al., 2015), as well as FTCs could alter soil properties and structure that induced the variation of soil hydraulic conductivity (Moghadas et al., 2016; Zhang et al., 2016). After FTCs, K_s of BCs and BS were both reduced, while the difference between them was shrunken (from 66% to 53%). *Ks* of BCs was significant and positive correlated with clay content, while it was negatively corrected with WR and sand content. We have found that FTCs had the significant effects on the percentage of water-stable aggregates of 1–5 mm particle size, clay content (0–2 cm soil layer), WR and K_s. The broken up of aggregates after FTCs (Oztas and Fayetorbay, 2003; Xiao et al., 2019b, c) may be due to the frozen alternating with thaw causing the shrinking and expanding of pore space between aggregates and the internal space within aggregates (Li and Fan, 2014). Ma et al. (2021) indicated that FTCs increase the soil porosity through controlling the air content, whereas the water entrance weakens aggregate stability. After FTCs, the proportion of lager particle size was decreased, while the proportion of smaller particle size was increased, which limited water move in soil (Rossi et al., 2012). Clay particle is always considered a typical hydrophilic material, which is positively related to K_s.

BCs can fix sands, but the increase of macro water-stable aggregates and its own WR could induce the reduction of K_s. The low hydraulic conductivity may restrict precipitation convert to soil water, which

Table 2
Results of two-way analysis of variance, testing the effects of soil surface type (Biocrusts and bare sand), experiment treatments (Freeze-thaw cycles), and their interaction on percentage of soil water-stable aggregates ($D_{>5}$ and $D_{1\text{-}5}$), soil mean weight diameter (MWD), soil particle-size composition (Clay, Silt and Sand), saturated hydraulic conductivity (*Ks*), bulk density (BD) and water repellency (WR).

	Num DF	*F* value	*P* value	*F* value	*P* value	*F* value	*P* value
Sources		$D_{>5}$		$D_{1\text{-}5}$		MWD	
Type	1	590.08	<0.001	112.83	<0.001	671.31	<0.001
Treatment	1	0.33	>0.05	12.70	<0.05	0.10	>0.05
Type*Treatment	1	10.25	<0.01	0.16	>0.05	11.12	<0.01
Sources		$\text{Clay}_{0\text{-}2}$		$\text{Silt}_{0\text{-}2}$		$\text{Sand}_{0\text{-}2}$	
Type	1	1.02	>0.05	83.64	<0.001	71.45	<0.001
Treatment	1	4.26	<0.05	2.04	>0.05	2.58	>0.05
Type*Treatment	1	4.10	<0.05	0.10	>0.05	0.35	>0.05
Sources		$\text{Clay}_{2\text{-}5}$		$\text{Silt}_{2\text{-}5}$		$\text{Sand}_{2\text{-}5}$	
Type	1	1.16	>0.05	23.85	<0.001	20.38	<0.001
Treatment	1	0.23	>0.05	0.77	>0.05	0.72	>0.05
Type*Treatment	1	4.70	<0.05	1.11	>0.05	1.46	>0.05
Sources		*Ks*		BD		WR	
Type	1	107.38	<0.001	35.50	<0.001	32.88	<0.001
Treatment	1	39.96	<0.001	2.60	>0.05	5.13	<0.05
Type*Treatment	1	18.45	<0.001	0.00	>0.05	5.13	<0.05

Table 3
Correlations among the water repellency, percentage of soil water-stable aggregates ($D_{>5}$ and $D_{1\text{-}5}$), soil mean weight diameter (MWD), soil particle-size composition (Clay, Silt and Sand) and bulk density (BD).

	WR	$D_{>5}$	$D_{1\text{-}5}$	MWD	$\text{Clay}_{0\text{-}2}$	$\text{Silt}_{0\text{-}2}$	$\text{Sand}_{0\text{-}2}$	$\text{Clay}_{2\text{-}5}$	$\text{Silt}_{2\text{-}5}$	$\text{Sand}_{2\text{-}5}$	BD
*Ks*1	−0.669*	0.833^{**}	−0.229	0.837^{**}	0.708^{**}	0.803^{**}	-0.821^{**}	0.807^{**}	0.762^{**}	-0.766^{**}	−0.642*
*Ks*2	-0.902^{**}	0.500	0.246	0.569	0.731^{**}	0.427	−0.459	0.752^{**}	0.559	−0.581*	−0.257
*Ks*3		0.303	0.004	0.268	0.221	0.456	−0.460	0.165	0.537	−0.515	-0.714^{**}
*Ks*4		0.205	0.148	0.160	−0.548	−0.506	0.710^{**}	0.357	0.526	−0.486	-0.860^{**}

Note: $D_{>5}$, $D_{1\text{-}5}$: proportion of soil water-stable aggregates of > 5 mm and 1–5 mm particle size; $\text{Clay}_{0\text{-}2}$, $\text{Silt}_{0\text{-}2}$ and $\text{Sand}_{0\text{-}2}$: proportion of clay, silt and sand in 0–2 cm soil depth; $\text{Clay}_{2\text{-}5}$, $\text{Silt}_{2\text{-}5}$ and $\text{Sand}_{2\text{-}5}$: proportion of clay, silt and sand in 2–5 cm soil depth; *Ks*1 and *Ks*3: Saturated hydraulic conductivity of biocrusts and bare soil before freeze–thaw cycles, respectively; *Ks*2 and *Ks*4: Saturated hydraulic conductivity of biocrusts and bare soil after freeze–thaw cycles, respectively. * Correlation is significant at the $p < 0.05$; ** Correlation is significant at the $p < 0.01$.

Table 4
Soil initial infiltration rate (IR) and steady infiltration rate (SIR) before freeze–thaw cycles in biocrusts and bare sand (Mean ± SD).

	IR (mm min^{-1})	SIR (mm min^{-1})
Biocrust	5.81 ± 0.88B	0.94 ± 0.13 A
Bare sand	9.01 ± 2.56 A	1.66 ± 0.61 A

Note: The different capital letters indicate the difference of infiltration rate between biocrust and bare sand ($p < 0.05$).

result in the ponding of water in surface soil layer, accordingly, evaporation was increased. This would be disastrous for vegetation restoration in water limited regions. We hypothesized that FTCs could influence WR of BCs and properties of soils underlying BCs, and then improve hydraulic conductivity. However, the obtained results refuted our expectations. This study suggested that FTCs further reduced the hydraulic conductivity, and mainly through altering WR of BCs and its underlying soil aggregates stability. The decreasing of hydraulic conductivity reduced the supply of meltwater to soil water reservoir and increased water evaporation in the period of winter and spring turn, which was a disadvantage to seed germination and vegetation growth in spring.

5. Conclusions

The existence of moss-biocrusts significantly increased macro water-stable aggregates and the percentage of clay and silt in its underlying soil and increased WR in surface soil layer. This study indicated that BCs and FTCs has the significant and negative effects on particle-size composition, water repellency and soil saturated hydraulic conductivity (K_s). Sand content and water repellency had significant negative effects on K_s, while the percentage of soil water-stable aggregates > 5 mm had the significant positive effects on $K_{s.}$ After freeze–thaw cycles, the percentage of soil water-stable aggregates > 5 mm was decreased, and K_s of moss-biocrusts further decreased. This study demonstrates that freeze–thaw cycles aggravate the negative effects of moss-biocrusts on hydraulic conductivity.

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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Authors' contributions

G.L.W. and Z.H. conceived the idea and designed the study; Z.H.,Y.B. W., J.X.Q., T.L. and J.L. performed the experiment and collected the data; Z.H. and Y.B.W. analyzed the data; G.L.W. and Z.H. led the writing of the manuscript with the help of M.L.V., Z.L., and K.Q. All authors contributed critically to the draft and gave final approval for publication.

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