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# Effects of differing coverage of moss-dominated soil crusts on hydrological processes and implications for disturbance in the Mu Us Sandland, China

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## Abstract:

To study the effects of biological soil crusts (BSCs) on hydrological processes and their implications for disturbance in the Mu Us Sandland, the water infiltration, evaporation and soil moisture of high coverage (100% BSCs), middle coverage (40% BSCs) and low coverage (0% BSCs, bare sand) of moss-dominated crusts were conducted in this study, respectively. The conclusions are as follows: (1) the main effects of moss-dominated crusts in the Mu Us Sandland on the infiltration of rainwater were to reduce the infiltration depths and to retain the limited rainwater in shallow soil; (2) moss-dominated crusts have no significant effects on daily evaporation when the volumetric water content at 4 cm depth in 100% BSCs (VWC4) was over 24.7%, on enhanced daily evaporation when the VWC4 ranged from 6.5% to 24.7% and on reduced daily evaporation when the VWC4 was less than 6.5%; and (3) decreasing the coverage of moss-dominated crusts (from 100% to 40%) did not significantly change its effects on infiltration, evaporation and soil moisture. Our results demonstrated that for the growth and regeneration of shrubs, which were dominated by *Artemisia ordosica* in the Mu Us Sandland, high coverage of moss-dominated crusts has negative effects on hydrological processes, and these negative effects could not be significantly reduced by decreasing the coverage of moss-dominated crusts from 100% to 40%. Therefore, for the sustained and healthy development of shrub communities in the Mu Us Sandland, it is necessary to take appropriate measures for the well-developed BSCs in the sites with high vegetation coverage in the rainy season. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS moss-dominated crusts; infiltration; evaporation; soil moisture; disturbance; Mu Us Sandland

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## INTRODUCTION

Biological soil crusts (BSCs) consist of soil microbes, algae, lichens, mosses, cyanobacteria and soil particles (Belnap and Lange, 2003). The biotic components of BSCs have strong endurance to extreme drought and heat and were widely distributed in arid and semi-arid regions (Belnap, 2003). The occurrence and development of BSCs had significant influences on hydrological processes in arid and semi-arid regions, such as rainwater infiltration (Chamizo *et al*., 2012a), runoff (Belnap, 2006) and evaporation (Chamizo *et al*., 2013). Furthermore, because the biotic components of BSCs improved soil physicochemical properties by their physiological and metabolic activities (Guo *et al*., 2008), and the special microstructure of BSCs (Zhang *et al*., 2006; Lan *et al*., 2012), BSCs enhanced soil fertility (Chamizo *et al*., 2012b), reduced water erosion (Rodriguez-Caballero *et al*., 2012) and wind erosion (Zhang *et al*., 2006), stabilized soil surfaces (Chaudhary *et al*., 2009) and accelerated the process of soil forming (Patrick, 2002). Thus, BSCs play an important role in arid and semi-arid ecosystems.

Different researchers hold different views on the effects of BSCs on infiltration, evaporation and soil moisture because of the differences in research areas, crust types and experimental methods that were used in the study of BSCs (Li *et al*., 2009). Some researchers believed that the presence of BSCs enhanced water infiltration (Barger *et al*., 2006) and increased soil water availability by increasing water flux resistance (Eldridge and Greene, 1994). Other researchers found that the development of BSCs exacerbated the decrease in soil moisture in deep layers (Gao *et al*., 2010). However, most studies of the influence of BSCs on water infiltration, evaporation and

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soil moisture have been conducted in arid regions, and limited research has been conducted on these aspects in the Mu Us Sandland where the annual average rainfall reached approximately 400 mm (Wu *et al.*, 2012). Exploring the effects of BSCs on infiltration, evaporation and soil moisture in the Mu Us Sandland is useful to identify the effects of BSCs on hydrological processes in this region and is also an important supplement to research on global BSCs.

Researchers have found that the coverage of BSCs reached 83.74% in the fixed sand dune in the Mu Us Sandland and that well-developed BSCs caused the death and degradation of *Artemisia ordosica* communities, which is dominant species in this region (Xiong *et al.*, 2011; Zhang *et al.*, 2013). From the view of improved soil water infiltration, reducing the waste limited rainwater and promoting ecological restoration in semi-arid regions, disturbance measurements were suggested for developed and intact BSCs (Bu *et al.*, 2013; Zhang *et al.*, 2013). However, BSCs have high effectiveness in controlling wind erosion, and they were extremely vulnerable to the disturbance (Zhang *et al.*, 2006; Bu *et al.*, 2013). The inappropriate type, intensity and occasion (e.g. seasonal condition) of BSC disturbance would aggravate the occurrence of desertification (Mario and Navar, 2000; Ponzetti and McCune, 2001; Zhang *et al.*, 2006). Moreover, despite many studies on the effects of the disturbance of BSCs on hydrological processes, the conclusions from different studies were inconsistent. For example, Chamizo *et al.* (2012a) reported that trampling disturbance, such as treading the crust patches 100 times (five rounds with 20 steps per round), increased the occurrence of runoff and infiltration in sites that were covered with undisturbed crusts more than in sites where the crusts were removed (Harper and Marble, 1988). On the contrary, Li *et al.* (2006) found that mechanical disturbances on crusts increased infiltration rates and substantially reduced the runoff from crust patches to shrub patches, which may cause annual rainfall that is insufficient to sustain the growth of shrubs (Li *et al.*, 2008). Because of the uncertainty of the effects of BSC disturbance on hydrological processes, ecological and pasture managers cannot determine the correct way of utilizing BSC resources (Li, 2005). Therefore, a study on the differing coverage of BSCs, which simulates the removal disturbance, on hydrological processes and discussion of their implications on disturbance would provide useful information about the optimal use of limited soil water resources and the management of BSC resources in the Mu Us Sandland.

We laid high coverage (100% BSCs), middle coverage (40% BSCs) and low coverage (0% BSCs, bare sand) of moss-dominated crusts on the soil column, which simulate removal disturbance in this study, and conducted a simulation experiment and positioning observation in the Mu Us Sandland to determine the effects of different coverage of moss-dominated crusts on infiltration, evaporation and soil moisture. Based on these analyses, we discussed the necessity and feasibility of BSC disturbance in the Mu Us Sandland.

## MATERIALS AND METHODS

### *Study sites*

This study was conducted in Gechougou, which is located in Shenmu County on the southeastern edge of the Mu Us Sandland, Shaanxi Province, China (38°10′–39°05′ N latitude, 109°40′–110°30′ E longitude). It is a semi-arid area with a typical continental monsoon climate. The mean annual precipitation is 440.8 mm, most of which (60–70%) occurs between July and September (Gao *et al.*, 2014). The average evaporation and average temperature are 2092 mm and 7.8 °C, respectively. The average wind velocity is 2.4 m/s with a maximum value of 19 m/s , and the wind direction is predominantly northwest. The soil is loose and infertile and can be classified as aeolian sandy soil (Zhang *et al.*, 2013). Associated with the sand dune fixation process, the xeric succession process in the Mu Us Sandland was divided into three stages: (i) annual and rhizomatous plant stages in active sand dunes, (ii) sub-shrub stage in semi-fixed sand dunes, and (iii) shrub stage in fixed sand dunes (Chen, 1983; Guo, 2000). *A. ordosica* grows on a wide range of sand dune stages; however, it is not common on active sand dunes, and it begins to decline in the fixed sand dune stages (Kobayashi *et al.*, 1995). BSCs, which are dominated by moss, are commonly founded in shrubs and shrub communities; algae are less prevalent. The moss identified in the study sites are *Bryum pallescens*, *Bryum recurvulum* Mitt., *Bryum argenteum* and *Barbula unguiculata* Hedw.

### *Preparation of crusted and bare sand*

Three bare sand (50 × 50 cm) sites and three moss-dominated crust sites (50 × 50 cm) were chosen in the field. The soil of each site was dug from 0 to 5, 5 to 15 and 15 to 25 cm depths. Sand soil was taken directly from top to bottom, and soil covered by moss-dominated crusts was taken after intact whole crusts were removed. The soil in the same depth of bare sand was mixed and placed into labelled plastic bags, as was the soil covered by crusts. Then, the soil and crusts samples were returned indoors.

A layer of 60 mesh (0.25 mm) stainless steel gauze was paved on the bottom of transparent acrylic column, and the holes on the side of transparent acrylic column were all sealed with tape. Packed soil samples were air-dried and sifted through a 1 mm sieve into the transparent acrylic column (26 cm length and 23.4 cm inner diameter) according to the order of 15–24, 5–15 and 0–5 cm. The moss-dominated crusts were laid on the soil column surface to achieve the following coverages of the soil surface: 0% (bare sand), 40% (40% BSCs) and 100% (100% BSCs) (Figure 1). The gaps between the crusts in the 40% BSCs treatment were carefully filled with soil from crust layers to simulate the removal disturbance. Each treatment was replicated three times. Table I shows the physical properties and initial moisture content of soil in the experiment. The crust thickness measured by a Vernier calliper was 1.61 ± 0.10 cm [mean ± standard error (SE), $n = 9$]. Table II showed the soil particle size of the bare sand and moss-dominated crusts (0–2 cm) measured by Mastersizer 2000E.

### *Infiltration measurement*

The infiltration experiment was conducted in a transparent acrylic column. A Mariotte bottle (10 cm inner diameter and 100 cm height) provided a continual and stable depth of ponding. The schematic diagram of the experimental setup was shown in Figure 2.

The infiltration process was determined by using the vertical infiltration method. To prevent the sand soil surface from being scoured with a crater, which affected the infiltration process, a layer of filter paper the same size as the of soil column surface was laid on the soil column. To rapidly form a water layer of 1 cm thickness on the soil surface, 450 ml of water was poured onto the soil surface quickly. At the same time, a Mariotte bottle began to supply water. The thickness of the water layer on the soil surface was stabilized at 1 cm. The water level of the Mariotte bottle and the depth of the wetting front in the soil column were recorded at 30 s intervals for the first 2 min and at 60 s intervals for succeeding minutes. The record ended when the wetting front arrived at the bottom of the transparent acrylic column. Water temperatures were recorded during the entire infiltration process.

### *Evaporation measurement*

Each soil column was placed in a plastic barrel (40 cm in diameter and 50 cm in height). Water was then poured along the wall of the plastic barrel, which made the water level flush with the surface of the soil column. When soil columns were saturated completely (after approximately 3 h), the soil columns were placed in a shady area and covered with a plastic sheet until the redundant water was drained. After that, all soil columns were placed in open land. To reduce the effects of direct sunlight on absolute values of daily evaporation, the soil column wall was enclosed by a sun-shading net. The soil columns were weighed at 8:00 h every day, with a precision of 1 g. The weight of the soil column loss 1 g was equivalent to the soil water loss 0.023 mm in the soil column. Soil columns were covered with plastic sheets during rainfall. The evaporation experiment ended when the daily evaporation rate became stable.

### *Soil moisture measurement*

During the evaporation experiment, the volumetric water content at depths of 4, 9, 14 and 19 cm in the soil

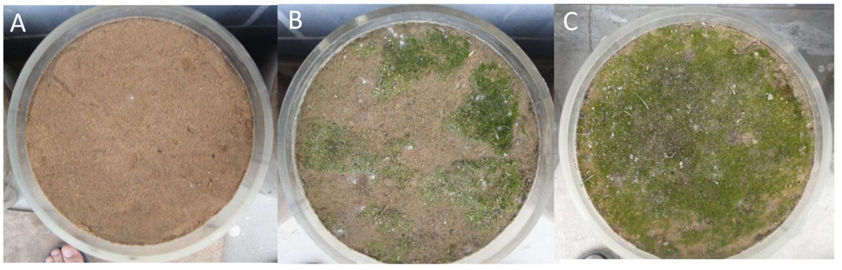


Figure 1. Photo showing the coverage of three treatments [0% biological soil crusts (BSCs), 40% BSCs and 100% BSCs] in the study. Moss-dominated crusts covered 0% (0% BSCs, A), 40% (40% BSCs, B) and 100% (100% BSCs, C) of the soil surface

Table I. Initial soil water content and physical properties of the three samples (0% BSCs, 40% BSCs and 100% BSCs)

| Treatments | 0% BSCs | | | 40% BSCs | | | 100% BSCs | | |
|---|---|---|---|---|---|---|---|---|---|
| Depths (cm) | 0–5 | 10–15 | 15–20 | 0–5 | 10–15 | 15–20 | 0–5 | 10–15 | 15–20 |
| Bulk density (g/cm$^3$) | 1.6 | 1.6 | 1.6 | 1.6 | 1.7 | 1.7 | 1.7 | 1.6 | 1.6 |
| Initial soil water content (%) | 0.2 | 0.2 | 0. 3 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 |
| Capillary porosity (%) | 18.3 | 20.7 | 17.8 | 37.0 | 24.2 | 20.4 | 35.0 | 22.6 | 19.9 |

The moss-dominated crusts covered 0% [0% biological soil crusts (BSCs)], 40% (40% BSCs) and 100% (100% BSCs) of soil surface.

 

Table II. The soil particle size of shallow layers (0–2 cm) in bare sand (BS) and moss-dominated biological soil crusts (BSCs)

| | <0.002 mm | 0.002–0.02 mm | 0.02–0.2 mm | 0.2–2 mm |
|---|---|---|---|---|
| BSCs | 0.7% | 2.0% | 35.1% | 62.2% |
| BS | 0.3% | 1.1% | 12.5% | 86.1% |

column was measured by a probe-type time-domain reflectometer (TRIME-IPH) at 9:00 h every day.

*Data analysis*

The infiltration rate was calculated for the equation (Dong *et al*., 2010):

$$f(t)_{Ti} = \frac{(h_i - h_{i-1})A_1}{A_2 \Delta t_i}$$

where $f(t)_{Ti}$ is the infiltration rate at $i$ time and at $T$ °C in mm/s; $h_i$ and $h_{i-1}$ are the height of water level in the Mariotte bottle at $i$ and $i - 1$ times, respectively, in cm; $A_1$ is the section area of the Mariotte bottle in cm$^2$; $A_2$ is the section area of soil column in cm$^2$; and $\Delta t_i$ is the time difference between $i$ time and $i - 1$ time in s.

To eliminate the effects of temperature on the infiltration rate, the infiltration rates at different water temperatures were transformed into standard values (under 10 °C) by using the equation (Hu *et al*., 2005):

$$f(t)_{10} = \frac{f(t)_T}{0.07 + 0.03T}$$

where $f(t)_{10}$ is the infiltration rate at 10 °C in mm/s, $f(t)_T$ is the infiltration rate at $T$ °C in mm/s, $T$ is the temperature in the infiltration experiment in °C, and 0.07 and 0.03 are the certain coefficients.

The cumulative infiltration was calculated for the equation (Wang *et al*., 2014):

$$C_i = \frac{A_1 h_i}{A_2}$$

where $C_i$ is the cumulative infiltration at $i$ time in cm; $h_i$ is the height of the water level in the Mariotte bottle at $i$ in cm, $A_1$ is the section area of the Mariotte bottle in cm$^2$, $A_2$ is the section area of the soil column in cm$^2$.

Data were expressed as the means ± standard error. Data were analysed for significance by using the $t$-test, one-way analysis of variance and least significance difference test by SPSS 12.0.

## RESULT AND ANALYSIS

*Effects of moss-dominated crusts on infiltration rates*

The growth and development of moss-dominated crusts resulted in a remarkable reduction in the infiltration rate.

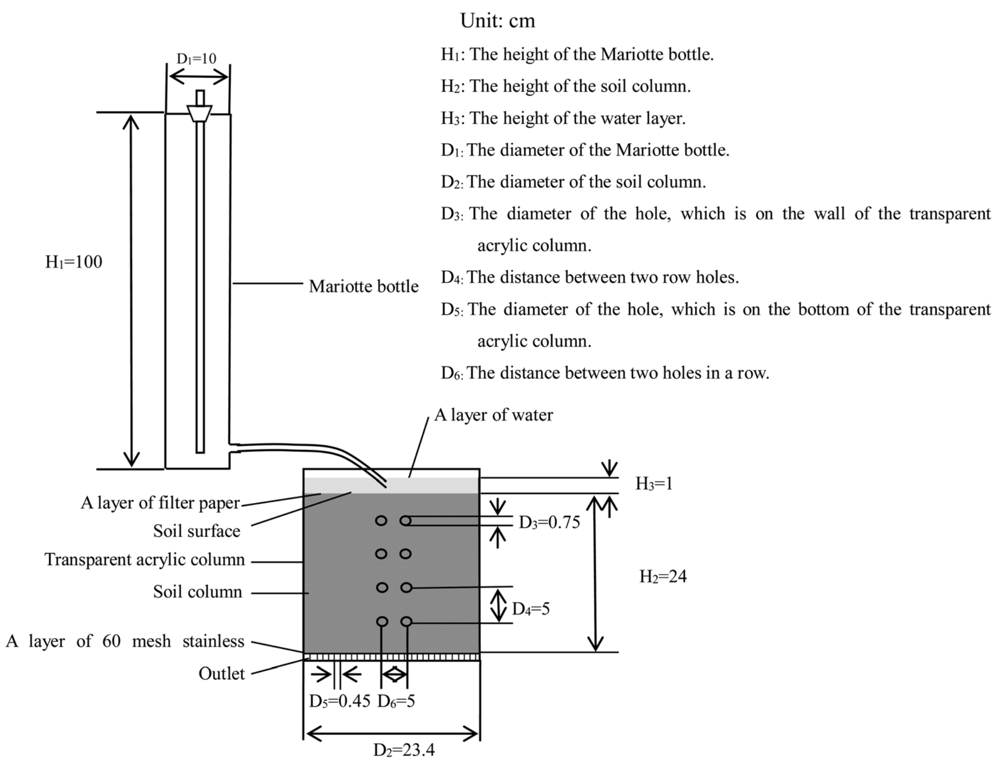


Figure 2. Schematic representation of the infiltration experimental setup used in the study

Figure 3 showed the graphs of infiltration rates measured during the infiltration experiments for three soil examples analysed in this paper. The infiltration rate at 60 s was chosen to represent the initial infiltration rate because the formation of a steady water layer on the soil column surface at the start of the infiltration experiment affected the accuracy of the infiltration rate. The initial infiltration rate of 100% BSCs decreased by 22.2% and 61.5% compared with that of 40% BSCs and 0% BSCs, respectively. The initial infiltration rate in 40% BSCs decreased by 50.5% compared with that in 0% BSCs. Significant differences were found between 100% BSCs and 0% BSCs ($p < 0.01$), whereas no significant differences were found between 100% BSCs and 40% BSCs ($p > 0.05$).

### *Effects of moss-dominated crusts on the driving velocity of the wetting front*

Figure 4 showed the wetting front characteristics of three treatments. The results indicated that the wetting front depth of 0% BSCs was greater than that of 100% BSCs and 40% BSCs at the same time. For example, the wetting front depths of 0% BSCs, 40% BSCs and 100% BSCs arrived at 23.3, 12.0 and 11.0 cm at 180 s, respectively. The wetting front velocity of 100% BSCs decreased by 8.1% and 52.7% compared with that of 40% BSCs and 0% BSCs, respectively. The wetting front velocity of 40% BSCs decreased by 48.6% compared with that of 0% BSCs. A significant difference was found between 100% BSCs and 0% BSCs ($p < 0.01$), whereas no significant difference was found between 100% BSCs and 40% BSCs ($p > 0.05$). This finding indicates that moss-dominated crusts could extend the duration of rainwater infiltration into sand soil and reserve water in shallow soil.

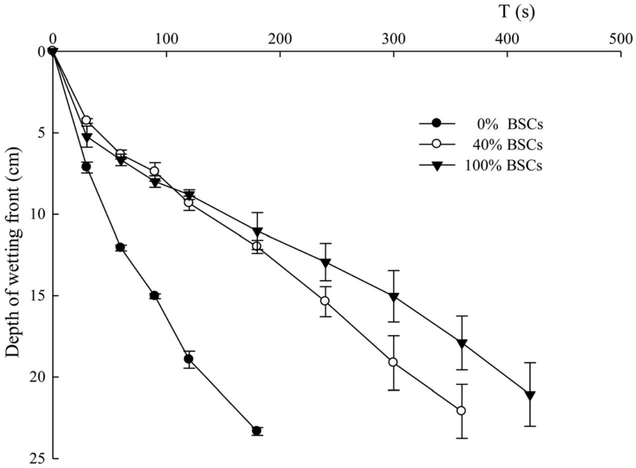


Figure 4. The depth of the wetting front of the three treatments [0% biological soil crusts (BSCs), 40% BSCs and 100% BSCs] during the infiltration experiment. Moss-dominated crust covered 0% (0% BSCs), 40% (40% BSCs) and 100% (100% BSCs) of the soil surface

### *Effects of moss-dominated crusts on cumulative infiltration*

Figure 5 showed the dynamic changes in cumulative infiltration with time. The results indicated that compared with bare sand, cumulative infiltration was significantly reduced by moss-dominated crusts and it was negatively correlated with the coverage of moss-dominated crusts ($p = -0.90$). The cumulative infiltration of 100% BSCs decreased by 26.1% and 61.5% compared with that of 40% BSCs and 0% BSCs, respectively. The cumulative infiltration in 40% BSCs decreased by 47.9% compared with that in 0% BSCs. The difference among three treatments had reached significant level ($p < 0.05$).

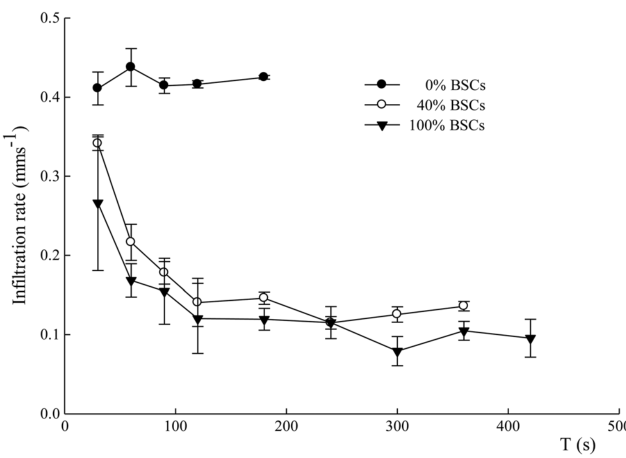


Figure 3. The infiltration rate of the three treatments [0% biological soil crusts (BSCs), 40% BSCs and 100% BSCs] during the infiltration experiment. Moss-dominated crusts covered 0% (0% BSCs), 40% (40% BSCs) and 100% (100% BSCs) of the soil surface

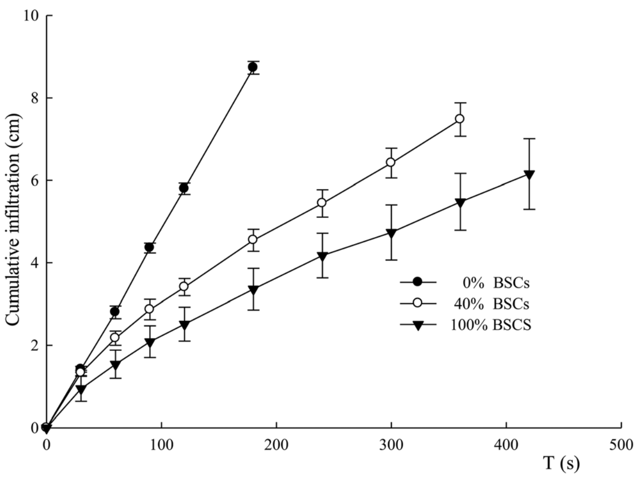


Figure 5. The cumulative infiltration of the three treatments [0% biological soil crusts (BSCs), 40% BSCs and 100% BSCs] during the infiltration experiment. Moss-dominated crust covered of 0% (0% BSCs), 40% (40% BSCs) and 100% (100% BSCs) of the soil surface

 

*Effects of moss-dominated crusts on daily evaporation*

The daily evaporation characteristics of moss-dominated crusts during the evaporation experiments for the three treatments were in Figure 6. The results showed that the daily evaporation of the three treatments decreased with time and ultimately tended to be stable. The effects of moss-dominated crusts on daily evaporation could be divided into three stages based on the volumetric water content in 4 cm depth in 100% BSCs (VWC4). When VWC4 exceeded 24.7% (first two days), the daily evaporation of 40% BSCs increased by 4.9% and 5.7% compared with that of 100% BSCs and 0% BSCs, respectively, and the daily evaporation increased by 0.8% in 100% BSCs compared with that in 0% BSCs. The statistical analysis indicated that the difference among the three treatments did not reach a significant level ($p > 0.05$). When VWC4 ranged from 6.5% to 24.7% (from the 3rd to the 11th day), the daily evaporation in 100% BSCs increased by 0.2% and 60.9% compared with that in 40% BSCs and 0% BSCs, respectively, and the daily evaporation increased by 60.5% in 40% BSCs compared with that in 0% BSCs. The statistical results confirmed that the difference between 100% BSCs and 0% BSCs was significant ($p < 0.05$), whereas the difference between 100% BSCs and 40% BSCs was not significant ($p > 0.05$). When VWC4 was less than 6.5% (from the 11th to the 22nd day), the daily evaporation in 100% BSCs decreased by −0.9% and 25.9% compared with that in 40% BSCs and 0% BSCs, respectively, and the daily evaporation reduced by 26.6% in 40% BSCs compared with that in 0% BSCs. A significant difference was found between 100% BSCs and 0% BSCs ($p < 0.01$), whereas no significant difference was found between 100% BSCs and 40% BSCs ($p > 0.05$).

*Effects of moss-dominated crusts on cumulative evaporation*

Figure 7 showed the dynamic changes in cumulative evaporation with time. In the entire evaporation process, cumulative evaporation in 100% BSCs and 40% BSCs increased by 30.1% and 31.0% compared with that in 0% BSCs, respectively. Cumulative evaporation increased by 0.7% in 40% BSCs compared with that in 100% BSCs. Statistical results confirmed that the difference between 100% BSCs and 0% BSCs was significant ($p < 0.05$), whereas the difference between 100% BSCs and 40% BSCs was not significant ($p > 0.05$).

*Effects of moss-dominated crusts on the soil moisture profile*

Figures 8–10 showed the soil moisture of the three treatments in different depths at the initial, middle and later stages of the evaporation experiment. The results indicated that the effects of moss-dominated crusts on the soil moisture profile also changed with the VWC4. In the first day of the evaporation experiment, when VWC4 was 31.4% (Figure 8), the soil moisture in 4 and 9 cm depths of 100% BSCs increased by 32.3% and 6.9% compared with that in 0% BSCs, respectively. By contrast, the soil moisture in 14 and 19 cm depths of 100% BSCs decreased by 5.7% and 10.0% compared with that of 0% BSCs, respectively. The statistical results indicated that the difference between 100% BSCs and 0% BSCs reached a significant level ($p < 0.05$), and no significant difference was found between 100% BSCs and 40% BSCs ($p > 0.05$). On the tenth day of the evaporation experiment, the soil moisture in 9 cm depth of 100% BSCs and 40% BSCs was less than that in 0% BSCs for the first time when VWC4 was 7.4% (Figure 9). Although

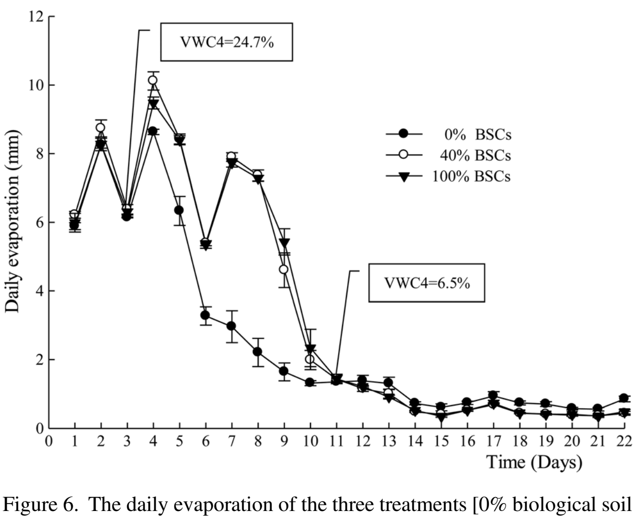


Figure 6. The daily evaporation of the three treatments [0% biological soil crusts (BSCs), 40% BSCs, 100% BSCs] during the evaporation experiment. Moss-dominated crust covered 0% (0% BSCs), 40% (40% BSCs) and 100% (100% BSCs) of the soil surface. VWC4, volumetric water content in 4-cm depth in 100% BSCs

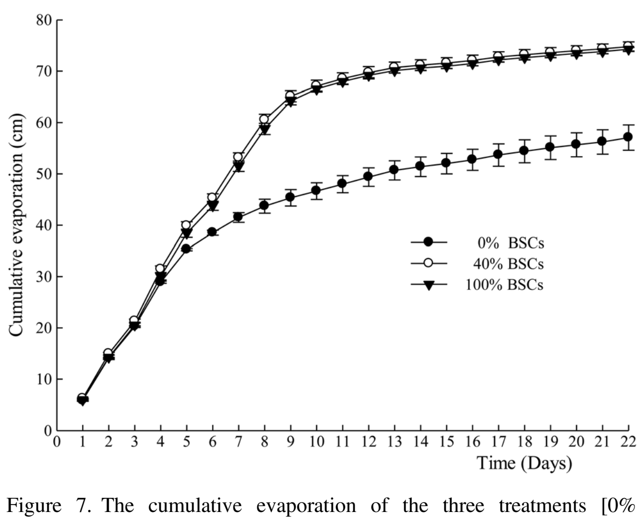


Figure 7. The cumulative evaporation of the three treatments [0% biological soil crusts (BSCs), 40% BSCs and 100% BSCs] during the evaporation experiment. Moss-dominated crusts covered 0% (0% BSCs), 40% (40% BSCs) and 100% (100% BSCs) of the soil surface

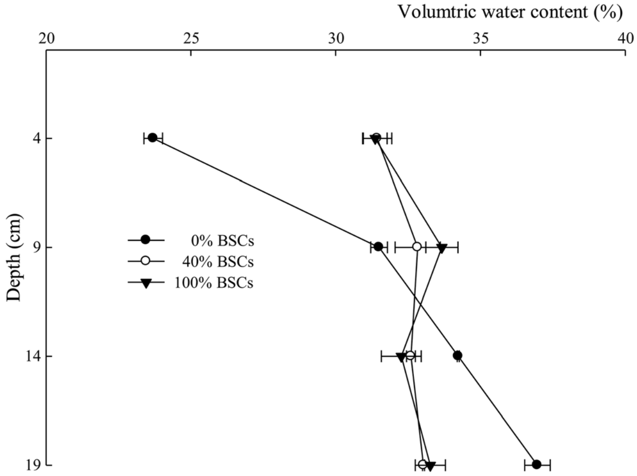


Figure 8. Soil moisture on the vertical profile of the three treatments [0% biological soil crusts (BSCs), 40% BSCs and 100% BSCs] on the first day of the evaporation experiment. Moss-dominated crusts covered 0% (0% BSCs), 40% (40% BSCs) and 100% (100% BSCs) of the soil surface

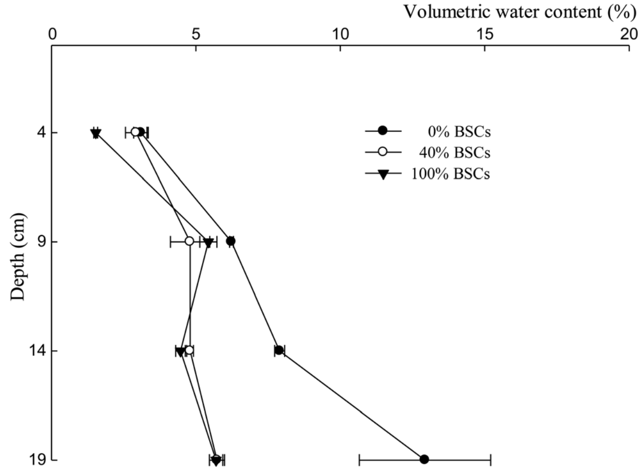


Figure 10. Soil moisture on the vertical profile of the three treatments [0% biological soil crusts (BSCs), 40% BSCs and 100% BSCs] on the 22nd day of the evaporation experiment. Moss-dominated crusts covered 0% (0% BSCs), 40% (40% BSCs) and 100% (100% BSCs) of the soil surface

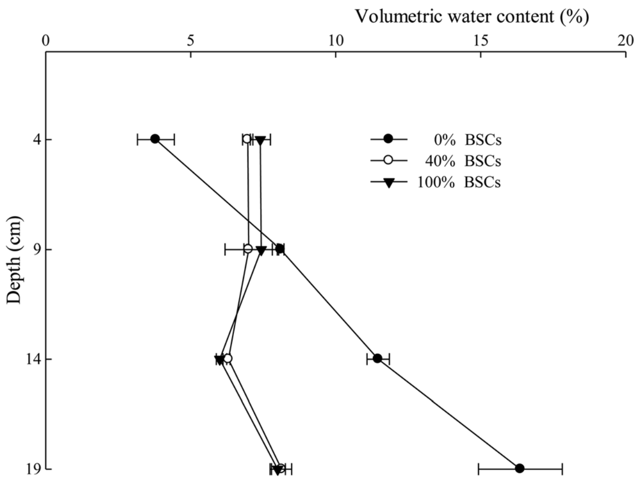


Figure 9. Soil moisture on the vertical profile of the three treatments [0% biological soil crusts (BSCs), 40% BSCs and 100% BSCs] on the tenth day of the evaporation experiment. Moss-dominated crusts covered 0% (0% BSCs), 40% (40% BSCs) and 100% (100% BSCs) of the soil surface

no significant difference was found between 40% BSCs and 100% BSCs, 40% BSCs showed lower soil moisture in 4 cm depth than that in 100% BSCs.

As the soil moisture decreased, the ability of 100% BSCs and 40% BSCs to improve soil moisture in topsoil (4 cm) decreased gradually. On the 22nd day of the evaporation experiment, when the VWC4 was 1.5% (Figure 10), the soil moisture at 4, 9, 14 and 19 cm depths of 100% BSCs decreased by 50.5%, 12.8%, 43.5% and 55.9% compared with that of 0% BSCs, respectively. The statistical results confirmed that the reduction in the soil moisture profile by 100% BSCs was significant (except for the 9 cm depth). The soil moisture at 4, 9, 14 and 19 cm depths of 100% BSCs reduced by 47.7%, 13.2%, 6.9% and 0.6% compared with that of 40% BSCs, respectively. Differences in soil moisture between the two treatments were not statistically significant ($p > 0.05$).

These findings reveal that the presence of moss-dominated crusts on dune surfaces could enhance soil moisture in topsoil (0–9 cm) during rainy seasons, whereas the soil moisture could be reduced in dry seasons. Rainy seasons in the Mu Us Sandland mainly occur from July to September; therefore, most of the year is in the dry season. Therefore, in the long run, moss-dominated crusts in the Mu Us Sandland reduced soil moisture, especially in deeper soil.

## DISCUSSION

### *Effects of moss-dominated crusts on infiltration and evaporation*

The results of infiltration showed that the stable infiltration rate of the intact moss-dominated crusts was approximately 0.1 mm/s (Figure 3), which was much higher than any rainstorms in semi-arid regions. Therefore, few runoff events occurred in desert regions during the dry period (Li *et al.*, 2001), and the reduction in the rate of rainwater infiltration caused by moss-dominated crusts has little effect on the soil water reservoir. However, the proportion of silt and clay in crust and subsurface soil (0–2 cm) increased during the period of crust and subsurface soil development (Li *et al.*, 2002). During rainfall events, dust that had fallen on the crust sealed the matrix porosity of the BSCs (Shachak and Lovett, 1998; Barger *et al.*, 2006) and swelled microbial exudates; for example, extracellular polymeric substances clogged the pore space (Fischer *et al.*, 2010). These effects reduced the hydraulic conductivity of the soil surface and prolonged the time at which water remained on the surface of the BSCs (Wu *et al.*, 2012). Moreover, the soil water-holding capacity of crusts and subsurface soil was greater (Duan *et al.*, 2004) than that of bare sand, and BSCs in the Mu Us Sandland can absorb a large amount of water when BSCs are dry (Wu *et al.*, 2012). Consequently, the main effects of moss-dominated crusts in deserts on rainfall infiltration are to reduce infiltration depths and to retain the limited rainfall in shallow soil. These results were similar to those found in previous studies (Wang *et al.*, 2007; Gao *et al.*, 2010).

Conflicting views existed on the evaporative effects of BSCs. For example, Zhang *et al.* (2007) found that evaporation in BSCs plots was higher than in shifting sand, and Kidron and Tal (2012) reported similar findings. However, Eldridge and Greene (1994) noted that the formation of BSCs reduced the evaporation rate. The results in our research showed that the effects of moss-dominated crusts on evaporation did not simply enhance or reduce it. The effects of moss-dominated crusts on evaporation can be divided into three stages according to the VWC4. The daily evaporation between sand soil and soil covered by moss-dominated crusts did not show significant differences when VWC4 was over 24.7%, which can be attributed to the evaporation that was mainly controlled by atmospheric evaporability when soil has adequate water. When VWC4 ranged from 6.5% to 24.7%, the daily evaporation of soil covered by moss-dominated crusts was higher than that of sand soil. These results were in accordance with Chamizo *et al.* (2013). This phenomenon could be caused by (1) moss-dominated crusts enhancing the water-retention capacity of topsoil (Li *et al.*, 2010b), which caused the soil covered by crusts to provide more soil water for evaporation; (2) soil covered by crusts prolonging the time at which rainwater can be kept on or at the soil surface (Gao *et al.*, 2010) and the upper soil covered by crusts promoting capillary movement to the surface, which increased the risk of water being evaporated; and (3) the formation of the dry layer in uncrusted soil surfaces reducing the evaporation rate; however, the formation of the dry layer in crusted soil was prevented by BSCs (Xiao *et al.*, 2010). When VWC4 was less than 6.5%, moss-dominated crusts could significantly reduce daily evaporation because the dry moss-dominated crusts absorbed water better than sand soil (Zhang *et al.*, 2008), which reduced the loss of soil moisture. Thus, moss-dominated crusts can accelerate the loss of soil moisture through evaporation under abundant precipitation and inhibit evaporation under little or no precipitation.

*Effects of disturbance on infiltration and evaporation*

The results of infiltration showed that decreasing the coverage of BSCs (moss-dominated crusts) had no significant influence on infiltration rates. In contrast to our results, Li (2011) reported that the infiltration rate could be significantly increased when the coverage of BSCs was reduced to 22% (17% coverage of algae and 5% of mosses). This difference was caused by the different dominant types of crust in the two studies. Therefore, the effects of BSC disturbance on the infiltration rate can be affected by the BSCs component, which has been reported from Chamizo *et al.* (2012a). Our results showed that cumulative infiltration could be significantly increased when the coverage of crusts decreased from 100% to 40%, which was different from the results of the initial infiltration and wetting front velocity. These findings suggested that the differences in the index in the research could lead to contradictory results when determining the effects of BSCs on infiltration.

Literature focusing on the effects of BSC disturbance on evaporation processes was limited and often contradictory. Xiao *et al.* (2010) demonstrated that the effects of BSCs on evaporation were mainly dependent on soil texture. Thus, removal of the moss-dominated crusts did not effectively reduce soil moisture evaporation in comparison with undisturbed moss crusts (*Chamizo et al.*, 2013). Our results supported this finding. The finding from the Tengger Desert showed that the BSC disturbance reduced cumulative evaporation by 20.1% compared with that in sand dunes (Li *et al.*, 2006). Meng *et al.* (2011) also reported that moderate sand mulching decreased evaporation significantly. The reason for these contradictory results could be related to the difference in BSC components and patterns of disturbance. Further research is still needed to explore the mechanisms of the effects of the disturbance of moss-dominated crusts on evaporation processes.

*Necessity and feasibility of BSC disturbance*

The Mu Us Sandland is known as one of the ‘kingdoms for shrubs and sub-shrubs’ in the global temperate zones in arid environments (Li and Xiao, 2007), where shrublands are dominated by *A. ordosica* (Kobayashi *et al.*, 1995). Previous researchers have found that shrub communities play an important role in ecological restoration in semi-arid regions. First, shrubs create significant ‘islands of fertility’, which could improve soil properties and facilitate vegetation recovery by controlling desertification processes (Zhao *et al.*, 2007). Second, shrubs are highly tolerant to moderate burial, denudation and drought in semi-arid regions (Li *et al.*, 2010a), and they have great wind erosion resistance (Yang *et al.*,

 

2014) because of their dense branches significantly decreasing near-surface wind speed (Guo, 2000). Third, shrubs have an important role in maintaining or augmenting herbaceous species richness in semi-arid regions (Zhao *et al*., 2007). In summary, shrubs not only have been used by local people as food for livestock and protection against desertification (Li and Xiao, 2007) but also contribute to the maintenance of ecological health and biodiversity in the Mu Us Sandland (Yang *et al*., 2008). Therefore, both ecological and pasture managers expected that the shrub communities could sustain healthy development in this region (Guo, 2000). Without the protection of shrubs, near-surface wind speed in the semi-fixed and fixed sand dunes would be inevitably increased, and herbaceous species clearly could not reduce the near-surface wind speed because of their short height. Naturally, the risk of wind erosion would be rapidly increased. Moreover, herbaceous species with shallow roots are unable to survive in the moving sand environment and die from sand burial (Li *et al*., 2004), which is a common phenomenon in the Mu Us Sandland. Once the soil surface in the sites only covered by herbaceous species was destroyed by severe denudation or other disturbance, the sand dunes, which had been fixed, would become active again (Guo, 2000), causing the degeneration of the ecological environmental in this region. Our study demonstrated that moss-dominated crusts in the Mu Us Sandland enhanced soil moisture in shallow soil (0–9 cm) during rainy seasons and accordingly reduced the soil moisture in deeper soil, and the root system of *A. ordosica* in the Mu Us Sandland was mainly found from 10 to 30 cm below the ground surface in semi-fixed and fixed sand dunes (Kobayashi *et al*., 1995). Therefore, in the long run, well-developed and intact BSCs in this region would be adverse to the growth and regeneration of *A. ordosica* communities. This view was supported by other studies in the same region. For example, Wu *et al*. (2012) found that the development of BSCs decreased soil moisture in deep layers and caused the death and degradation of *A. ordosica* in the Mu Us Sandland (Kobayashi *et al*., 1995; Xiong *et al*., 2011). Although rainwater, which was retained in the shallow soil by moss-dominated crusts, could provide more soil moisture for the growth of shallow-rooted herbaceous species and biotic components of BSCs, in view of the rule of ecological succession and anti-wind erosion in the Mu Us Sandland, the degradation of large-scale shrub communities is undoubtedly adverse to the stability of ecosystems in this region. To improve soil water infiltration, increase the soil moisture in deeper soil and promote ecological succession in the Mu Us Sandland, it is necessary to take disturbance measurements on developed and intact BSCs in this region in the premise of no wind erosion exacerbation.

Our research found that reduced coverage of moss-dominated crusts significantly increased cumulative infiltration. Although the difference in the initial infiltration rate and wetting front velocity between 40% BSCs and 100% BSCs was not statistically significant, these indexes in 40% BSCs were all higher than in 100% BSCs. This view was supported by a previous study (Chamizo *et al*., 2012a) as was the fact that the grazing disturbance of moss-dominated crusts in the Mu Us Sandland could lead to greater infiltration depths after rainfall (Xiong *et al*., 2011). These events are important in increasing available water to shrubs. Besides, the research in the Mu Us Sandland found that moderate disturbance (for example, grazing) could promote the growth and regeneration of *A. ordosica* communities (Guo *et al*., 2000). Therefore, it is believed that ideal disturbance would be beneficial for the dynamic balance of *A. ordosica* communities in the Mu Us Sandland (Zhang *et al*., 2013). Previous studies have shown that BSCs were sensitive to disturbance (Ponzetti and McCune, 2001); the cover, abundance and composition of BSCs were all affected by disturbance (Warren and Eldridge, 2003), and improper disturbance would aggravate the occurrence of desertification (Mario and Navar, 2000; Ponzetti and McCune, 2001). However, the stable and high coverage of *A. ordosica* communities, which has a great ability to protect soil from wind erosion (Yang *et al*., 2014), has formed in semi-fixed and fixed sand dunes in the Mu Us Sandland (Xiong *et al*., 2011). BSCs are commonly found in *A. ordosica* communities and are growing with increasing plant cover (Zhang *et al*., 2010). Our earlier study showed that moderate disturbance on moss-dominated crusts in the Mu Us Sandland did not rapidly increase wind erosion when the shrub coverage reached a relatively high degree (>50%) (Yang *et al*., 2014). Through the wind tunnel experiment, Chen *et al*. (1996) demonstrated that soil moisture was one of the most important factors influencing resistance to wind erosion and that increasing soil moisture could rapidly reduce wind erosion. Most (60–70%) of the annual precipitation in the Mu Us Sandland occurred from July to September (Gao *et al*., 2014), and the features of this period are low wind speed, relative high soil moisture and flourish vegetation. Thus, appropriate disturbances of BSCs from July to September could not increase wind erosion. More importantly, damaged BSCs grew more significantly than intact crusts under watery conditions (Cooper *et al*., 2001), and fragmentation of the BSCs, which were caused by grazing disturbance, would be partially compensated by an increase of newly formed BSCs (Hiernaux *et al*., 1999). Therefore, disturbance of BSCs would not rapidly increase wind erosion or cause the degradation of ecosystems in the Mu Us Sandland. To improve soil moisture in deeper soil and promote the sustained and healthy development of shrub communities in the Mu Us Sandland, land mangers could take appropriate measures for well-developed and intact BSCs in fixed sand dunes with high coverage of plants from July to September, as long as the occasion and regions of disturbance are appropriate

It is worth noting that the present research is the only study on the effects of different coverage of moss-dominated crusts that simulates removal disturbances on hydrological processes. There are many types of disturbance, which include grazing, trampling, burial and burning in the field, and the appropriate intensity and manner of disturbances for disturbing BSCs to improve soil moisture are not clear at present. A comprehensive study that considers the intensity and manner of disturbances of BSCs on wind erosion and soil moisture is needed to fill these research gaps.

## CONCLUSION

In this study, we examined the infiltration, evaporation and soil moisture of 100% BSCs, 40% BSCs and 0% BSCs in the Mu Us Sandland. The results demonstrate that the development of moss-dominated crusts has significant effects on hydrological processes in the Mu Us Sandland. The specific results are as follows. First, the main effects of moss-dominated crusts in the Mu Us Sandland on the infiltration of rainwater were to reduce infiltration depths and to retain the limited rainwater in shallow soil; in particular, the initial infiltration rate, wetting front velocity and cumulative infiltration in 100% BSCs decreased by 61.5%, 52.7% and 61.5% compared with those in 0% BSCs, respectively. Second, the effects of moss-dominated crusts on evaporation can be divided into three stages according to the VWC4. Moss-dominated crusts have no significant effects on daily evaporation when the VWC4 was over 24.7%, on enhanced daily evaporation when the VWC4 ranged from 6.5% to 24.7% or on reduced daily evaporation when the VWC4 was less than 6.5%. During the entire evaporation process, accumulative evaporation in 100% BSCs increased by 30.1% compared with that in 0% BSCs. Third, moss-dominated crusts in the Mu Us Sandland enhanced soil moisture in shallow soil during rainy seasons and reduced soil moisture in deeper soil. In the long run, moss-dominated crusts in the Mu Us Sandland reduced soil moisture, especially in deeper soil. Fourth, decreases in the coverage of moss-dominated crusts (from 100% to 40%) did not significantly change its effects on infiltration, evaporation and soil moisture.

From these results, we concluded that for the growth and regeneration of shrub communities, which were dominated by *A. ordosica* in the Mu Us Sandland, moss-dominated crusts have negative effects on hydrological processes, and these negative effects could not be significantly reduced by decreasing the coverage of moss-dominated crusts from 100% to 40%. Therefore, for the sustained and healthy development of *A. ordosica* communities in the Mu Us Sandland, it is necessary to take appropriate measures for the well-developed BSCs in the sites with high coverage of vegetation in the rainy season.

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