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Effect of sand burial on the subcritical water repellency of a dominant moss crust in a revegetated area of the Tengger Desert, Northern China

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Abstract: Sand burial is a ubiquitous disturbance that influences the ecological and hydrological properties of moss crusts in many sandy desert areas. There is little available information regarding the effect of sand burial on the water repellency (WR) of moss crusts in desert areas. Therefore, this study evaluated the effects of sand burial (sand depths of 0 (control), 0.5, 1, 2, 4 and 10 mm) followed by three simulated precipitation regimes (through applying 4 and 6 mm, 2 and 3 mm, and 1 and 1.5 mm of distilled water at 8-day intervals in spring and autumn, respectively) on the WR of a widespread moss crust dominated by *Bryum argenteum* Hedw. in a revegetated area of the Tengger Desert, China. The results showed moss crust WR remained subcritical during the whole experiment, and that it considerably decreased immediately after sand burial, even though the values of WR were significantly higher in autumn than those in spring under the same treatment ($p < 0.05$). Furthermore, the depth threshold (TD) values for sand burials that reduced WR to zero were 1 and 2 mm in spring and autumn, respectively. After a recovery period of nearly one-season (72 days), the WR of the moss crust significantly increased ($p < 0.05$). In addition, sand burial had two separate effects on moss crust WR. Specifically, shallower sand burial (burial depth less than 0.5 mm) increased moss crust WR, whereas deeper sand burial (burial depth exceeds 0.5 mm) decreased it. The TD values also significantly increased to 2 and 4 mm in spring and autumn, respectively. These findings about the effects of sand burial on moss crust WR provide additional information that can be used to better understand the influence of sand burial on moss crust colonization and maintenance in arid sand-burial-stressed ecosystems, and to help explain why there are some contrasting viewpoints on biocrust WR.

Keywords: Water repellency; Sand burial; Moss crust; Precipitation.

INTRODUCTION

Biological soil crusts (biocrusts) are a ubiquitous bio-cover in many desert ecosystems, and their colonization and development can profoundly alter soil morphological, hydrological, and ecological processes and functions (Bowker et al., 2013; Kidron, 2019; Li, 2012). Over the past few decades, many studies have revealed that these changes are heavily determined by the inherent components of the biocrust, ambient environmental factors, and disturbances (Weber et al., 2016).

Moss crusts are an essential biocrust type that are dominated by moss species. Moss crusts are typically in the highest and latest successional stage among surface-dwelling cryptogams, such as cyanobacteria, green algae, and lichen. They also have a greater ability to maintain and enhance the stability and fertility of many arid and semiarid desert ecosystems (Jia et al., 2018; Kidron and Benenson, 2014; Kidron et al., 2010). Recently, moss crusts have attracted the attention of biologists, ecologists and hydrologists (Weber et al., 2016), and it is increasingly accepted that water acquisition plays a critical role in their survival and ecological performances in water- limited arid areas. Therefore, many hydrological parameters have been employed to explain the ecological and hydrological processes and effects that occur when moss crusts are present.

Hydrophobicity or water repellency (WR), is a soil property that prevents free water from entering the pores of dry soil (Tillman et al., 1989; Urbanek et al., 2007). Some exploratory studies on moss crust WR have been conducted to evaluate its effects with infiltration, runoff, and other ecohydrological processes. However, there is still an ongoing debate about the existence and strength of moss crust WR (Kidron, 2019). For example, Kidron et al. (1999) found that WR was not a natural biocrust (including moss crust) surface property under field conditions, whereas subcritical and even slightly WR was detected on dry surfaces when they were subjected to prolonged continuous moisture in the laboratory. Similar contrasting results were recorded for coastal and desert crusts (Kidron and Büdel, 2014).

Moss crusts are very different from the other biocrust types in that they produce an erect-growing, waxy caulidium material on the crust surface. Moreover, the caulidium generates the WR properties of moss crusts from the origin or occurring requirement of WR (Jordán et al., 2013; Kidron and Büdel, 2014). By contrast, hydrophobic organic matter incorporated into the soil surface is generally responsible for the WR properties associated with cyanobacteria and some lichen crusts (Breckle et al., 2008; Kidron and Büdel, 2014). In addition, moss crusts typically have higher water contents (Kidron et al., 2010; Kidron and Benenson, 2014), a finer soil texture, and richer organic matter. Their other microenvironmental characteristics are also stronger (Li, 2012). These differences may affect WR directly or indirectly (Yang et al., 2014). Therefore, moss crust WR research should be treated with caution. Another needs to be noted is that disturbance was not equally considered across the different studies.

Sand burial is a common disturbance encountered by moss crusts in many desert areas because they are small in size and inhabit the soil surface (Jia et al., 2008, 2014, 2018). Sand burial can change WR-related soil temperature, moisture, and nutrients in the micro-environment (Jia et al., 2008, 2014; Maun, 1998, 2008). It can also change the physiology and growth of moss crusts (Jia et al., 2008, 2014, 2018). Therefore,

it is important to assess and quantify the influence of sand burial on moss crusts WR, while, up to date, little information is available regarding the effect of sand burial on moss crust WR in desert areas. The water repellency of sand particles is considerably lower than moss caulidium (Lichner et al., 2013; Yang et al., 2014). Therefore, our initial hypothesis was that sand burial would significantly reduce moss crusts WR. The effects of sand burial on moss crusts are both depth- and moisture-dependent according to our previous study (Jia et al., 2018). Therefore, to test the hypothesis, the WRs of a typical moss crust dominated by *Bryum argenteum* Hedw., a pioneer species in the Shapotou revegetated area of the Tengger Desert, was measured immediately and after a one-season recovery period by simultaneously subjecting them to six depths of sand burial and three rainfall regimes.

MATERIAL AND METHODS

Shapotou revegetated area is located at the southeastern fringe of the Tengger Desert (37°28′N, 105°00′E, elevation = 1339 m above mean sea level). It belongs to a steppified desert zone and is a transitional ecotone between desert and oasis. The typical landscape is large and dense, and contains reticulate barchan chains of sand dunes. The natural vegetation is dominated by *Hedysarum scoparium* and *Agriophyllum squarrosum*, which cover approximately 1% of the surface. The mean annual temperature is 10.6°C, with extreme minimum and maximum temperatures of –25.1°C and 38.1°C. The mean annual precipitation is 180.2 mm, the mean annual wind velocity is 2.9 m/s, and the mean annual number of dust storm days is 59 days (Jia et al., 2018; Li, 2012).

To ensure the smooth operation of the Baotou–Lanzhou Railway in the sand dune area, a vegetation protective system was initially established in 1956 by constructing straw checkerboards and planting xerophytic shrubs along the railway line. These areas were further expanded in 1964, 1981, and 1987. After the sand surface became relatively stabilized, biocrust biota colonized and developed on the sand surface and further contributed to the stabilization of the soil surface. Amongst the diverse biocrust organisms that were present, *B. argenteum* successfully colonized the revegetated area as a pioneer species and became widespread with coverage exceeding 70% on the windward slopes and low lying interdunes.

Although sand burial stress decreased along with the colonization and growth of *B. argenteum*, it still inevitably buries *B. argenteum* crusts to various depths when the wind blows in spring, because during this period, the wind speed is usually at its highest level and precipitation is lower. Crust burial may however take place also in summer and autumn when precipitation is slightly higher and the wind speed is lower following animal activity i.e., burrowing by ants, lizards, and rabbits (Jia et al., 2018; see Fig. 1).

The sampling methods and the *B. argenteum* crust sand burial + precipitation treatments were the same as in Jia et al. (2018). First, 108 cylindrical PVC dishes (104-mm diameter, 12-cm height) were used to collect intact moss crusts (85 cm^2, 10-cm thick), which contained 100% *B. argenteum* in late February and late August (about 10 days before the experiments began in spring and autumn) from the interspaces between shrubs in the revegetated area established in 1981. Then, they were transported and placed below the ground surface under rain shelters that were 2 m high. They were randomly divided into three water supply groups by applying distilled water in three artificial rainfall regimes at 8-day intervals in spring (4, 2 and 1 mm for the average amount of rain for this season, half the amount of rain and quarter the amount of rain, respectively) and autumn (6, 3 and 1.5 mm for the average amount of rain for this season, half the amount of rain and quarter the amount of rain, respectively). Each experiment lasted for 72 days, i.e. 9 sprinklings, which imply respectively a total of 36, 18 and 9 mm for the average, half and quarter amount of rain for the spring and a total of 54, 27, and 13.5 mm for the average, half and quarter amount of rain for the autumn, respectively. Following the sprinkling experiments, dried sand equivalent to 0

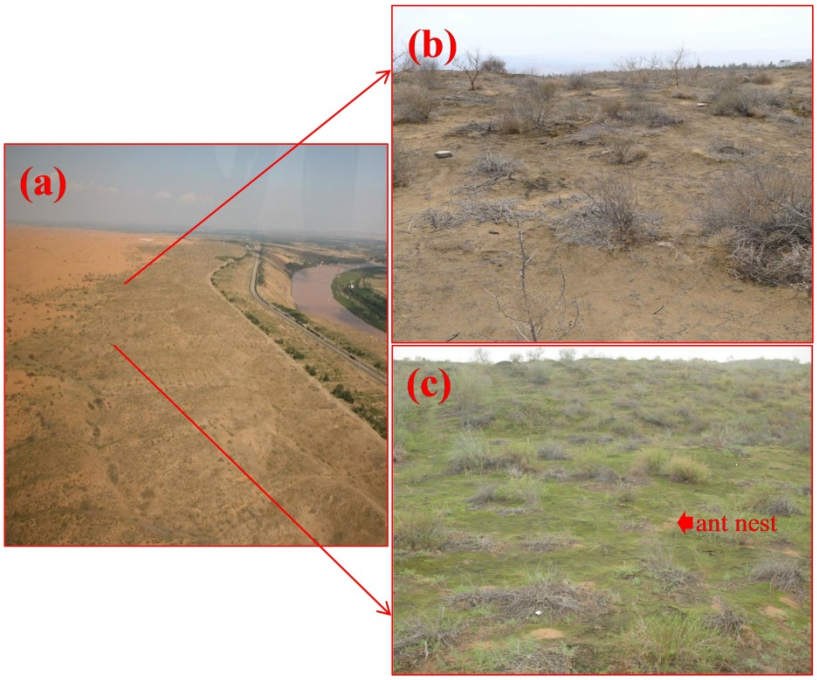


Fig. 1. Main landscape of the Shapotou revegetated area in the Southeastern edge of the Tengger Desert (a), where moss crust dominated by *Bryum argenteum* Hedw. flourish and recurrently being buried by sand particles to various depths through wind blowing sand in spring (b) and animal activities in summer and autumn (c).

(control), 0.5, 1, 2, 4, and 10 mm was distributed gently and evenly over crusts that had been subjected to each of the water-supply subgroups described above, respectively. The prescribed sand burial depths and quantities of water applied were selected based on actual sand burial depths and precipitation levels observed during the period of 1990–2010 (Li et al., 2012) in the study area. Spring and autumn experiments were carried out from 10 March and 1 September, respectively. Water repellency assessments were conducted immediately after the sand burial treatment (before the first irrigation) and at the end of the spring/ autumn sprinkling experiments (Fig. 2).

The water drop penetration time (WDPT) method (Yang et al., 2014) was used to determine the WRs of the samples. Five drops (50 μL) of distilled water were placed on the plane surface of each sample. The time taken for the drops to penetrate the crust was recorded and the mean times for each sample were recorded.

The WR persistence level was classified using a modified classification system adopted from Dekker et al. (2001) and Lamparter et al. (2006): non–water repellency (WDPT, < 1 s); subcritical WR (WDPT, 1–5 s), slightly (WDPT, 5–60 s), strongly (WDPT, 60–600 s), severely (WDPT, 600–3,600 s), and extremely (WDPT, > 3,600 s) WR.

A one-way analysis of variance (ANOVA) was used to test for any significant difference ($p < 0.05$) in the data using SPSS 21 software (SPSS Inc., Chicago, IL, USA). When the ANOVA revealed that there were significant differences present ($p < 0.05$), the differences between each sample were evaluated using LSD post-hoc multiple comparisons at the 95% confidence level.

RESULTS AND DISCUSSION

The colonization and development of moss on the surface of a sand dune induces a multitude of modifications to morphological, ecological and hydrological surface properties, such as surface roughness (Zhao et al., 2017), texture and organic matter (Li et al., 2017), albedo and temperature (Kidron and Tal, 2012; Zhang et al., 2017), moisture and vesicular porosity (Li et al., 2012), pore clogging and swelling of organic crust components (Kidron et al., 1999; Kidron and Benenson, 2014). Individually or collectively, these factors can change the moss crust water repellency (WR) (Yang et al., 2014). The WR of a typical moss crust dominated by *B. argenteum* Hedw. in the Shapotou revegetated area of the Tennger Desert was always < 5 s during the whole experiment, although the corresponding values for WR in autumn were significantly higher than those measured in spring (all $p < 0.05$, Fig. 3). The moss crust WR in the study area was subcritical according to the modified Dekker et al. (2001) and Lamparter et al. (2006) classification systems. This is in agreement with Yang et al. (2014), who investigated the same area, and Keck et al. (2016), who studied in the Negev Desert. Although Keck et al. (2016) maintained that the water drop penetration time (WDPT) method was not the best choice for detecting subcritical WR, we found that it was sufficiently sensitive to detect the in *B. argenteum* crust WR after it had been buried under different depths of sand (Figs. 2, 3 and 4).

In agreement with our initial hypothesis, the deposition of sand immediately lowered the WR of the *B. argenteum* crust in both spring and autumn (all $p < 0.05$) regardless of the rainfall regimes applied (Fig. 3). The dual effects of sand burial on moss crust WR were apparent when the crust was allowed to recover for 72 days. The results showed that the 0.5 mm sand burial depth increased the moss crusts WRs, which was inconsistent with our initial hypothesis. A recovery period clearly increased WR resistance to burial and this became more apparent as the water supply increased (all $p < 0.05$, Fig. 4). The thresholds of depth of sand burial that pulled down WR to zero (TD) were 1 and 2 mm (before recovery), and 2 and 4 mm (after recovery), in spring and autumn, respectively. This indicated that moss crust WR is more resistant to sand burial in autumn than in spring, and can be enhanced when the moss is subjected to a certain period of recovery.

In the Shapotou revegetated area, the moss crust develops from cyanobacterial or lichen crusts in a successional sequence (Li, 2012). Therefore, the excretion of hydrophobic substances, such as exopolysaccharides, by cyanobacteria or some lichen species is not the main cause of moss crust WR. Moss caulidiums are typically erect-growing and protrude above the soil surface. Therefore, it is the waxy material on the surface that is the main cause of WR, which means that the reduction in WR after sand burial can easily be explained. The sand cover is mainly from wind-blown sources or animal activities (such as nesting and burrowing, Fig. 1). The non-repellent sand particles that cover or adhere to the surface of the waxy material on the surface of moss caulidium, inevitably decrease WR. Furthermore, the decrease in surface roughness (Zhao et al., 2017), reduced albedo and increased temperature (Jia et al., 2014; Kidron and Tal, 2012; Zhang et al., 2017), and decreased evaporation (Jia et al., 2014; Meng et al., 2011) and thus elevated moisture content (Kidron and Tal, 2012), caused by sand burial, may also claim on their importance in the immediate reduction effect of sand burial on WR (Fig. 3). The results from this study fully supported this reasoning (Fig. 2), but further elaborate research is needed to better understand this process. The sand particles on the surface of the moss caulidium can also be pulled down vertically by raindrop. Therefore, WR should recover to some degree after rainfall. Consistent with Yang et



Fig. 2. Water repellency phenomena on the surfaces of *B. argenteum* crust before (a) and after (b) sand burial.

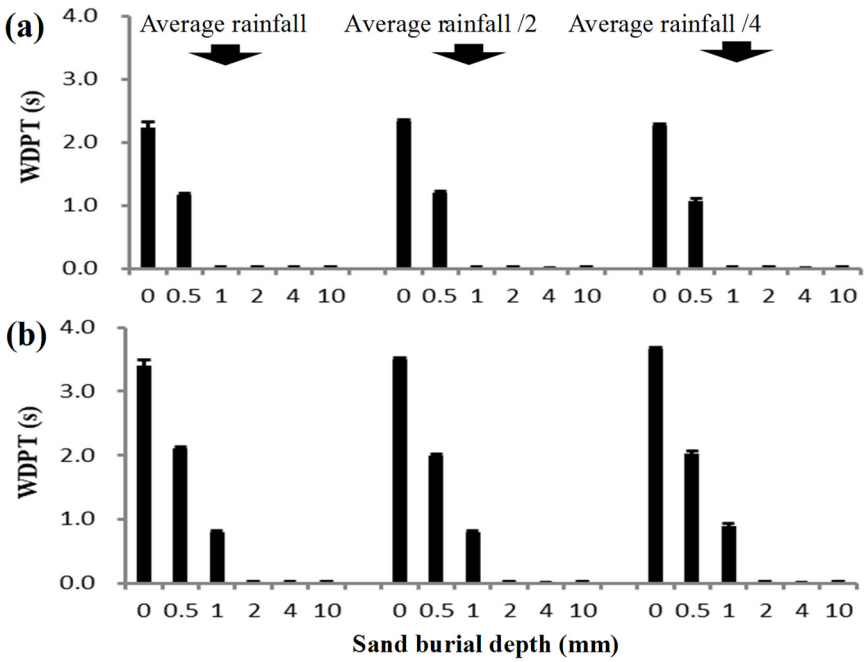


Fig. 3. Variations of initial repellency of *B. argenteum* crust buried with different depths of sand (0 (control) 0.5, 1, 2, 4, and 10 mm) prior to the sprinkling experiments in spring (a) and autumn (b). Bars represent one SE.

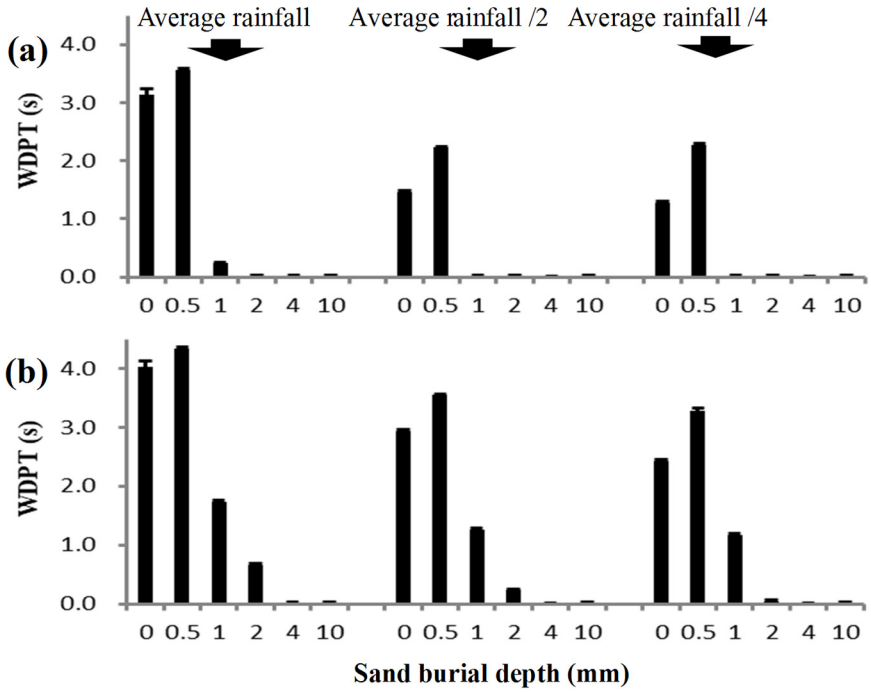


Fig. 4. Variations of water repellency of *B. argenteum* crust buried with different depths of sand (0 (control), 0.5, 1, 2 4, and 10 mm) under three rainfall amount (average, average/2 and average/4) treatments for 72 days in spring (a) and autumn (b). Bars represent one SE.

al. (2014), the WR results after rainfall (Fig. 4) can help explain why WR is higher after rainfall. The longer moss crust was subjected to prolonged moisture (the increased rainfall supply), the greater the WR under the same depth of sand burial. The findings about the influence of sand burial on moss crust WR may help explain some of the differences in the previously published results. For example, the biocrust samples taken for WR measurement by Kidron et al. (1999) may have been subjected to repeated covering by sand, which meant that they would have been previously buried by sand (or dust) particles before the biocrusts were sampled. Therefore, WR did not appear. However, the sand (or dust) particles were pulled down and thus the biocrust could recover from burial when they were subjected to prolonged continuous moisture (by stimulating rainfall) in the laboratory. This would enhance WR, which potentially led Kidron et al. (1999) to record subcritical and slightly WR for the crusts in Laboratory but not in the field. Similar explanations may also be used to explain the contrasting results between coastal and desert crusts (Kidron and Büdel, 2014).

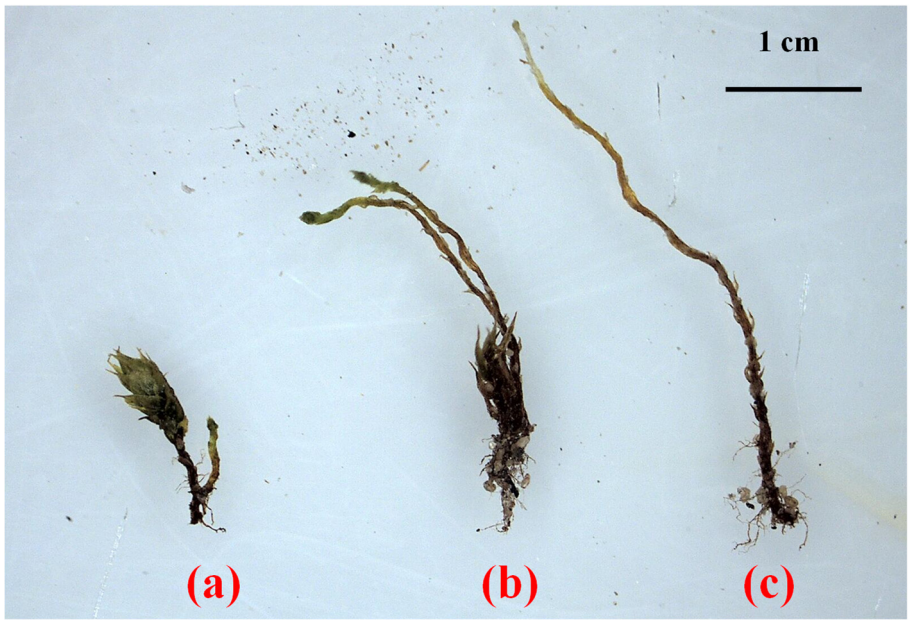


Fig. 5. The typical morphological changes of *B. argenteum* individual before (a) and after 2-mm (b) and 4-mm (c) sand burial.

Yang et al. (2014) also recorded the temporal changes in *B. argenteum* crust WR in the same study area as we used after using the same WDPT method. They attributed these changes to the physiological and biochemical processes in the moss that occurred during wetting and drying cycles. The similar changing trends for chlorophyll a content, PSII photochemical efficiency, regeneration potential, and shoot upgrowth under the same sand burial and rainfall treatment, may partially explain the changes in WR after sand burial when the mosses were subjected to a 72 days' recovery (Jia et al., 2018). However, the spaces within a moss crust that can be used to embed the over-burial sand particles are limited and are soon fully filled with additional sand particles as the burial depth increases, which is also evidenced by the crust coverage (Jia et al., 2008, 2014, 2018). Therefore, the overlying sand particles in the deep sand burial treatment reduced WR to a level that could not be detected by the WDPT method. *B. argenteum* has a strong shoot elongation capacity. However, even when its apexes protruded above the sand surface in the 4 mm sand burial (Fig. 5), the size of the moss caulidium shrank sharply, which enlarged the soil porosity. This meant that no water repellent effects were recorded.

Moss crusts typically ranks the highest and latest successional stage among diverse biocrust types across the Tengger Desert and other similar arid and semiarid sandy desert ecosystems across the globe (Jia et al., 2018; Kidron and Benenson, 2014; Kidron et al., 2010). This means that moss crusts are the highly water-dependent and sensitive to environmental factor changes (Jia et al., 2008, 2014, 2018). The results from this study were in agreement with Keck et al. (2016), who suggested that that the subcritical WR of moss crusts may only affect water redistribution on a microscale and has little influence on the ecosystem as a whole. The reduction in subcritical moss crusts WR after sand burial may further support this viewpoint. The lower WR after burial clearly increased the threshold rainfall amount/intensity needed to initiate runoff, and this increase will also affect the processes and consequences of soil moisture redistribution at the microscale. For example, more moisture will be partitioned to the moss caulidium and earlier in time due to the lower WR under burial, which would alleviate the negative effects of deep-sand burial and drought on physiological activity and growth (Jia et al., 2018). This additional mechanism may further improve the colonization, development and maintenance of biocrust mosses in arid sandy ecosystems. These overall improvements may suggest that the role of sand burial in sandy ecosystems may be underestimated because sand burial seems to positively affect moss crust colonization, succession and recovery processes (Jia et al., 2008, 2014, 2018). However, it also leads to the associated changes in hydrological characteristics (including dewfall and WR), and morphological and ecological properties (Jia et al., 2014; Maun, 1998, 2008; Meng et al., 2011; Zhao et al., 2017). These changes caused by sand burial may singly or collectively influence the emergence and growth of vascular plants, vegetation dynamics (Li et al., 2010), animal activity (Li, 2012) and diversity, and the structure of soil microorganism communities (Grishkan et al., 2015). They may also determine the structure and function of the whole ecosystem to a larger extent than was previously imagined.

CONCLUSION

The treatments applied to moss crusts during this study were six sand burial depths (0 (control), 0.5, 1, 2, 4, and 10 mm) combined with three simulated rainfall regimes (application of 4 and 6 mm, 2 and 3 mm, and 1 and 1.5 mm of distilled water at 8-day intervals in spring and autumn, respectively) over two seasons. We evaluated the effects of sand burial on water repellency (WR) by a typical moss crust dominated by *Bryum argenteum* Hedw. in a revegetated area of the Tengger Desert, China. The results indicated that the most important sand burial effects on the subcritical WR of the moss crust were burial-depth and burial-time dependent. Furthermore, a recovery period after burial had considerable positive effects on WR. Generally, the moss crust WR significantly decreased immediately after sand burial, and TD values for sand burial that reduced WR to zero were 1 and 2 mm, in spring and autumn, respectively. After a recovery period that lasted nearly a season (72 days), the results showed that sand burial had dual effects on moss crust WR. First, shallower sand burial (burial depth less than 0.5 mm)

increased the moss crust WR, whereas deeper sand burial (burial depth exceeds 0.5 mm) decreased it. Second, TD values significantly increased to 2 and 4 mm, in spring and autumn, respectively. This study helps explain why there have been contrasting reports on biocrust WR, and it clarifies the mechanisms underlying the colonization and maintenance of moss crust in arid sand-burial stressed ecosystems.

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