Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-579
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 21 November 2018

Hydrology and Earth System Sciences
Discussions
Open Access

Ecohydrological effectiveness of litter crusts in sandy ecosystem

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Abstract

Litter crusts are integral components of the water budget in terrestrial ecosystems, especially in arid areas. This innovative study is to quantify the ecohydrological effectiveness of litter crusts in desert ecosystems. We focus on the positive effects of litter crusts on soil water holding capacity and water interception capacity compared with biocrusts. Litter crusts significantly increased soil organic matter, which was 2.4 times the content in biocrusts and 3.84 times the content in bare sandy lands. Higher organic matter content resulted in increased soil porosity and decreased soil bulk density. Meanwhile, soil organic matter can help to maintain maximum infiltration rates. Litter crusts significantly increased the water infiltration rate under high water supply. Our results suggested that litter crusts significantly improve soil properties, thereby influencing hydrological processes. Litter crusts play an important role in improving hydrological effectiveness and provide a microhabitat conducive to vegetation restoration in dry sandy ecosystem.

Keywords: litter crusts; water-holding capacity; water infiltration; interface habitats; sand restoration

1. Introduction

Desertification is one of the most dangerous and threatening environmental problems to human in many areas of the word, and it leads to productivity reduction, biodiversity loss, and degradation of ecosystem functions and services (Huenneke et al., 2010). Increasing external pressures from human activities or climate change can cause desertification and influence the livelihoods of more than 25 % of the world's population (Kéfi et al., 2007). The occurrence of desertification, high air temperature, low soil humidity, and abundant solar radiation result in high potential evapotranspiration (Reynolds et al., 2007). Moreover, the soil nutrients are eroded by drastic water loss, and the soil fertility decreases with sand transport and dune burial, which consequently impede vegetation growth. It is a challenge for ecologists to stabilize the flow dunes and to transform them into stable, productive ecosystems. Therefore, desertification is "one of the most serious problems of our age" (Geist & Lambin, 2004).

With the increasing harm of desertification, some measurements of prevention and rehabilitation have been applied continuously. It is one of the widely popular restoration techniques to establish straw checkerboards on mobile sand dunes and eroded land. The straw checkerboards enhance the entrapment of dust on the surface of stabilized dunes, which facilitates topsoil development and makes it easier for biological soil crusts (biocrusts) to form (Li et al., 2006). Biocrusts are a soil surface community composed of microscopic and macroscopic poikilohydric organisms, are globally widespread, and are an important component of the soil community in many desert ecosystems (Grote et al., 2010; Gao et al., 2017). Biocrusts are highly specialized soil-surface groups that are an important component of desert ecosystems, especially in arid and semiarid regions. The important ecological functions of biocrusts include increasing soil aggregation and stability, preventing soil loss, increasing the retention of nutrients in the topsoil, and increasing soil fertility (Chamizo et al., 2012).

Large area afforestation is one effective measure that prevents and controls desertification in arid and semi-arid regions. Deciduous trees have been widely used in most of the sandy-land afforestation efforts. Afforestation can easily produce both biocrusts and litter crusts, which form by the litter that accumulates as a result of the common influences of wind and water (Jia et al., 2018). The interactions among precipitation, vegetation and litter crust are of care to hydrologists (Dunkerley, 2015). Litter crusts have the capacity to store water on their surface, which is filled by rainfall and emptied by evaporation and drainage (Guevaraescobar et al., 2007; Gerrits et al., 2010; Li et al., 2013). Previous studies have explored the transport processes of water in litter crusts, such as the interception of rainfall, the water-holding capacity (WHC) of litter materials, and the degree of retention within the litter (Makkonen et al., 2013; Dunkerley, 2015; Acharya et al., 2016). The plant-litter input from above- and below-ground composes the dominant source of energy and matter for a very diverse soil organism community that are linked by extremely complex interactions (Hättenschwiler et al., 2005). On one hand, litter crusts could improve microhabitat conditions (Chomel et al., 2016), and form soil organic matter (SOM) through biochemical and physical pathways (Makkonen et al., 2013; Cotrufo et al., 2015). On the other hand, litter crusts affect hydrological processes by serving as a barrier that prevents precipitation from directly reaching the soil and controls soil evaporation (Bulcock and Jewitt, 2012; Van Stan et al., 2017), which through two basic mechanisms: by the attenuation of radiation flux into and from the ground and by the increase in resistance to water flux from the ground (Juancamilo et al., 2010). The combined effects of these two mechanisms produced by litter crusts provide strong control of water transport. Consequently, interception by litter crusts is a key component of the water budget in some vegetated ecosystems (Gerrits et al., 2007; Bulcock and Jewitt, 2012; Acharya et al., 2016).

Prevention and control of soil and water erosion is an urgent issue to require solution on the Loess Plateau. The “Grain for Green Project” was implemented for controlling soil erosion and improving the ecological environment across a large portion of China. E.g. this project increased vegetation coverage on the Loess Plateau (China) from 31.6 % in 1999 to 59.6 % in 2013 (Chen et al., 2015). Consequently, the environmental conditions have improved and are suitable for the development and growth of crusts in the wind-water erosion crisscross region. Litter crusts and biocrusts were important contributors for the improvement of the surface microhabitat conditions. Although the importance of biocrusts in water processes has been recognized, the effect of litter crusts on sandy lands has received little attention. Therefore, the objectives of the study were (1) to determine the role of litter crust for soil properties and hydrological processes reflected by WHC, water interception capacity (WIC), water infiltration rate (WIR), and infiltration depth, and (2) to explore the dominant control factors of litter crust that affect water infiltration processes in sandy lands. The results will clarify the impact exerted by crusts on hydrological process, which protect the soil against erosion and improve soil microhabitats in sandy lands.

2. Materials and methods

2.1. Study sites

The experimental site was located in the southern Mu Us Desert (110°21′–110°23′ E, 38°46′–38°51′ N, a.s.l. 1080-1270 m), which is the water-wind erosion crisscross region of China. The climate is continental semi-arid monsoon climate, with a mean annual temperature of 8.4 °C. The minimum temperature is -9.7 °C in January and the maximum temperature is 23.7 °C in July. The mean annual precipitation is 437 mm (minimum of 109 mm and maximum of 891 mm), accounting for approximately 77 % of the rainfall occurs between June and September. The mean numbers of days that wind speed exceed Beaufort force 8 was 16.2, and mainly in spring. The soil type is aeolian sandy soil, which is prone to wind-water erosion. The sand, silt, and clay contents of the soil were 98.64, 1.32, and < 1.00, respectively (Wu et al., 2016). The areas with sandy loess soil, loose structure, and poor corrosion resistance were given priority. The Chinese government implemented several projects to reduce soil erosion and to prevent the drifting of sand as well as to improve the fragile ecosystem. Vegetation restoration has transformed the landscape from removable sand dunes to shrubby dunes, which was composed of fixed and semi-fixed sand dunes. The dominant natural vegetation was psammophytic shrubs and grasses (e.g., *Artemisia ordosica*, *Salix cheilophila*, *Lespedeza davurica*). In many sand dunes, *Populus simonii* was chosen for sand fixation.

2.2. Experimental design and soil sampling

This study was conducted in the wind-water erosion crisscross region, and *Populus simonii* was chosen as the main species for preventing wind and fixing sand. The region has suffered wind-water erosion in consecutive years due to its special geographical position, which has shaped its unique landscape characteristics. There is abundant plant litter gathered every year as a result of the interaction between wind transport and water erosion. Many litters were mixed with sand and eventually were fixed on the ground, this gradual process formed litter crusts. In this study, litter crust was defined as the crust formed by "all dead organic material made of both decomposed and undecomposed plant parts which are not incorporated into the mineral soil beneath" (Acharya et al., 2016). Soils covered by two types of crusts represented the most common crusts in this region. Biological soil crusts (biocrusts) were moss dominated, and the litter crusts were dominated by *Populus simonii* leaves. The litter crusts were divided into litter crust for 2 years (covered by only litter, LC2) and litter crust for 4 years (covered by litter and a semi-decomposed layer, LC4). For each crust type (LC2, LC4 and biocrusts) and bare sandy land (BSL, as control, Fig. 1), six experimental plots (> 100 m^2) were selected. Five sample sites as replication was selected in each experimental plot.

After a sample site was selected, the crust thickness was measured using a tape. The biocrust thickness was the total thickness of biocrust. In each sample site, the undisturbed crust layer was sampled using a cylindrical container with a diameter of 15 cm (with an area of 1.77 dm^{-2}). Moreover, biocrust evolution was represented by moss biomass per unit area. The soil on the mosses was removed by wet-sieving, and the moss plants were used as the biocrust samples. Various types of crusts from each plot were collected to determine the maximum water interception capacity (Max WIC) and maximum water-holding (storage) capacity (Max WHC). Ten samples were collected for analysis in each sample site and all samples collected at the same moment. Soil samples were collected using a soil drilling sample corer. The samples in the soil layers were collected at intervals of 0-3, 3-5, and 5-10 cm. Three replicates were taken from each sample site, and the same layer samples were mixed one sample for each plot. The bulk density (BD, g cm^{-3}) was measured using a soil bulk sampler (100 cm^{3}) stainless steel cutting ring, with three replicates in each plot. The soil total porosity (TP, %) was calculated by the (1-BD / PD) × 100, where BD represents soil bulk density (g cm^{-3}) and PD represents particle density (g cm^{-3}) which was assumed to be 2.65 g cm^{-3}. The samples were weighed and then oven-dried to a constant weight at 105 °C and then weighed to determine BD and soil water content (SWC, weight-%). The analyses in each sample site were repeated five times.

2.3. Water interception and holding capacity of litter crust

Water interception was defined as the amount of rainfall temporarily stored in the litter after drainage ceased (Guevaraescobar et al. 2007; Acharya et al. 2016). In the laboratory, collected litter was air-dried (65 °C to constant weight) and weighed to obtain the dry weight. To measure the amount of water intercepted by litter, a circular quadrat with a permeable mesh bottom (diameter of 15 cm) was used in such a way that the quadrat area was equal to the soil corer. The collected litter was then distributed uniformly over the entire quadrat. Simulated rainfall (rainfall intensity was 20 mm h^{-1}) was applied to the quadrats for successive 30 minutes and then weighed to determine the Max WIC (g dm^{-2}).

To determine the Max WHC, all crust samples were submerged in water for 24 hours. The samples were retrieved from the water and allowed to air dry and drain for approximately 30 min. Then, the samples were weighed as the maximum weight. The Max WHC (g dm^{-2}) was calculated as the difference between the maximum weight and the dry weight. The soil organic matter content (SOM) was determined by the dichromate oxidation method.

2.4. *Quantitative infiltration design*

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To investigate the influence of crusts on water infiltration, infiltration experiments using five different amounts of water were conducted in each plot. A cylinder with an inner diameter of 15 cm and a height of 15 cm was used for single-ring infiltrometry. Single-ring infiltrometry has been extensively applied as a basic infiltration measurement tool to measure the soil infiltration process (Ries & Hirt, 2008). The infiltration device was driven carefully to a depth of 2 cm by means of a plastic collar and a rubber hammer while avoiding produce leakage passages and guaranteeing the ring remains horizontal during installation. To prevent water leakage from the ring, the same soil materials were used to support the outside of the ring.

A paper board (5 × 5 cm) was placed in the ring above the crust and soil to avoid the risk of scouring when the water was added into the ring. The quantitative amount of water (500 mL, 1000 mL, 1500 mL, 2000 mL and 2500 mL in the study) was carefully poured on the paper board until it was 3 cm deep (the depth of 500 mL of water in the ring is close to 3 cm) as quickly as possible; this process was timed using a stopwactch. During the infiltration process, water was added by hand to maintain the water level within the ring. The time duration for the end of water infiltration in the ring was recorded to determine the water infiltration rate. The infiltration measurement of each water quantity was repeated 3 times in each sample site. After the infiltration experiment, the ring was removed, and then, a vertical soil profile was quickly excavated and the infiltration depth (cm) was directly measured using a tape.

Based on the water mass balance, the infiltration rate measured using the ring method was estimated from:

$$i = \frac{W}{A \times T} \times 10$$

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where *i* represents the infiltration rate (mm min^{-1}), *W* is the amount of water supplied for infiltration (mL), *A* is the infiltration area (cm^2), *T* is the infiltration time (min), and 10 is the conversion coefficient.

2.5. Statistical analyses

Two types of crusts (biocrust and litter crusts) were selected to determine the impact of crust components on hydrological process. Five plots of BSL were selected as controls. The normality of the data and the homoscedasticity were tested by the Kolmogorov-Smirnov and Levene's tests. In these comparisons, we conducted analysis of variance (ANOVA) on the data. Tukey's honestly test was used to analyse the differences in SWC, BD and TP in the different crust types at the different soil layers or the same soil layer. The differences in the crust thickness, Max WHC, and WIR of the crust types were tested using Tukey's honestly test. The difference in the Max WIC of LC2 and LC4 was detected using an independent *t* test. All differences were tested at the level of $p < 0.05$. Generalized linear model (GLM) analysis was used to explain the interactions between crust types and water supply in determining the water infiltration time, depth and rate. Correlation analysis was performed to explore the correlations among the different soil properties and the infiltration rates under different water supply-scenarios. All of these statistical analyses were completed using R statistical software v 3.4.2 (R Development Core Team 2017).

3. Results

3.1. Influence of crusts on soil properties

The contents of SOM were markedly higher in crust soils than in BSL (Fig. 2). The highest SOM content was in LC4 at the depth of 0-3 cm, which was 3.84 times the content in BSL and 2.4 times the content in biocrust. The SOM contents in the subsurface layers (3-10 cm) were 63.64-108.44 %, 18.18-20.83 % and 48.18-79.17 % greater under biocrust, LC2 and LC4, respectively, than under BSL. Within each type of crust, the SOM content clearly decreased with increasing soil depth. Over the 4-year period, the litter significantly reduced soil BD in both surface soil or subsurface soil. With the decrease of BD, soil TP was significantly higher in LC4 than in BSL and in biocrust.

There were differences between crust types in soil properties (Table 1). Compared to bare sandy land (BSL), both biocrusts and litter crusts significantly increased SWC in surface soil (0-5 cm). However, SWC showed a decreasing trend in crusts and showed an increasing trend in BSL with increasing soil depth. The SWC in BSL was 33 % higher in surface soil than in subsurface soil (5-10 cm), while the SWC in biocrusts and LC4 were 44 % and 18 % lower, respectively, in surface soil than in subsurface soil (5-10 cm).

3.2. Crusts improve hydrological effectiveness

The crust thickness, crust mass and Max WHC were obviously higher in the litter crust than in the biocrust (Fig. 3). Moreover, the mass of LC4 was 1.63 times higher than the mass of LC2 (Fig. 3B). The Max WHC values in LC4 and LC2 were 3.26 and 2.02 times that of biocrust (Fig. 3C), respectively. Meanwhile, the Max WIC in LC4 was 72.08 % higher than in LC2 (Fig. 3D). The analysis of the infiltration measurements showed that the effects of crust type and water supply on infiltration time, depth and rate were all significant (Table 2). The water infiltration rate of 500 mL water supply in various crust types was ranked LC4 > biocrust > BSL > LC2. The water infiltration rates of 1000 mL, 1500 mL, 2000 mL and 2500 mL water supplies in different crust types were ranked LC4 > LC2 > BSL > biocrust, and the rates in litter crusts and biocrust were significantly different (Fig. 4). The water infiltration depth increased significantly with water supply, but the trend of water infiltration depths was BSL > LC2 > LC4 > biocrust among the different crust types (Fig. 5).

3.3. Soil properties affect infiltration rates of different water supplies

Pearson's correlation analysis showed that the infiltration rates of different water supplies were significantly correlated with soil and crust properties (Fig. 6). Crust thickness and crust mass were significantly correlated with the infiltration rates of high water supply (> 1000 mL). The infiltration rate of 500 mL water supply was significantly positively correlated with TP in the 0-5 cm soil layer and SOM content in the 0-3 cm soil layer, while the infiltration rate of 500 mL water supply was significantly negatively correlated with BD in the 0-5 cm and 5-10 cm soil layers. The infiltration rates of the 1000 mL, 1500 mL, 2000 mL and 2500 mL water supplies were significantly correlated with the SWC in the 5-10 cm soil layer.

4. Discussion

Biocrusts influence many soil properties that are influenced the major ecosystem processes in drylands, such as nutrient cycling and hydrological processes (Gao et al., 2017). Previous studies have separately reported an increase in water retention and SOM content due to the presence of biocrusts (Chamizo et al., 2016). To our knowledge, few previous studies has reported how all these properties change in the litter crusts or how litter crust influence the hydrological processes in sandy lands. We examined all the changes in soil properties and hydrological functions in contrasting biocrusts and litter crusts in a desert ecosystem. Our results will fill these gaps in knowledge and demonstrate that litter crusts significantly influence soil properties and hydrological processes in sandy lands.

4.1. Influence of litter crusts on soil properties

Plant litter falls to the ground, and it assembles to develop a porous barrier that is structured by wind and water; this is called litter crust. The litter crust modifies the bidirectional fluxes of liquid water and water vapor and affects water evaporation from the soil by insulating the soil surface from the atmosphere and by intercepting radiation (Dunkerley, 2015; Van Stan et al., 2017). Litter crusts play an important role in changing soil bulk density and porosity, and they serve as a major source of soil organic matter in surface soils. The present study showed that litter crusts decreased the soil bulk density and increased soil porosity and SOM contents. Litter decomposition is an important ecosystem process that is critical to maintaining available nutrients. The SOM is formed through the partial decomposition and transformation of plant litter by soil organisms (Cotrufo et al., 2015). The fragments produced during litter decomposition can promptly associate with the topsoil layer. Some brittle litter residues move to the surface soils by water and wind transfer, and then, they form coarse particulate organic matter in the soil. The addition of organic matter increases soil porosity and decreases soil bulk density. The SOM is significantly higher in LC4 than in LC2. The decomposition times of the two litter crusts are a powerful explanation for this result. Over time, the increasing quantity of litter input forms a new microclimatic and promotes SOM accumulation in the surface soils (Liu et al., 2017). The Max WHC also contributes to the higher SOM in LC4. In general, the higher water content enhanced the decomposition rate in litter monocultures (Makkonen et al., 2013).

In our study, litter crusts and biocrust significantly increased surface soil moisture. However, the biocrust showed obvious desiccation in the subsurface soil layer and litter crusts did not happen. The higher moisture under biocrusts can be attributed to the biocrust-anchoring structures that bind soil particles and form mats on the soil surface; these properties strongly increase water retention at the soil surface (Chamizo et al., 2012). In arid and semi-arid regions during low-intensity rainfall, which is predominant in our study area, the rainfall is completely intercepted by biocrusts and cannot penetrate the crust to reach the subsurface soil. Moreover, the biocrusts decrease the subsurface soil water by consuming water during growth, which results in the desiccation of the subsurface soil layer. The change of soil properties (BD, porosity and SOM) caused by litter crust improved hydrological characteristics.

4.2. Effect of litter crusts on hydrological processes

The litter crusts can develop a significant thickness depending on wind, water and other factors. Our study showed that the ~5 cm litter crusts measured from 2-year and the ~9 cm litter crusts measured from 4-year-old *Populus simonii* forests. Our study also demonstrated that there are significant differences in the porosity of litter crusts between different ages, and that there are also differences in the interstitial spaces of litter crusts. These variations are major contributors that can cause the differences observed in the WIC of litter crusts. The WIC of litter crusts is an integral fraction for the effect of litter on infiltration and the development of surface runoff (Gerrits et al., 2010; Dunkerley, 2015). This is because the litter interception as a certain amount of water could satisfy the water requirement in early stage of infiltration and runoff (Gerrits et al., 2010). Litter crusts are continually broken down and decomposed by microbial activities. Therefore, the frequency of the movement and recombination of the litter crusts and other organic components can also be considered to influence the porosity and hydrological characteristics of litter crusts (Dunkerley, 2015). The maximum WHC of litter crust was 1.7 g water - g litter. However, the maximum volume of litter crust was 1540 cm^3, and only approximately 5 % of the available void space in the litter was occupied by water. This result indicates that water is retained in only smaller void spaces within the litter crusts and not in very large gaps, where gravity drainage would facilely arise because the dominant forces that contribute to water interception are gravity and cohesion (Li et al., 2013; Dunkerley, 2015). We immersed litter crusts in water for 24 hours and subsequently measured their weight gain. The results showed that the litter crust could store water which is equal to 154-200 % of their dry weight, so a large part of this storage water is determined by characteristics of the litter. In our study, the dominant litter crusts were formed by broadleaf litter (*Populus simonii* leaves), which played an important role in determining the water dynamics of the litter crusts (Sato et al., 2004). According to the findings of Li et al. (2013), the Max WHC showed a strong linear relationship with litter mass whether the litter was a monoculture or a mixture. The maximum mass in LC4 was 28.31 g dm^{-2}, which indicated the possibility of high levels of water storage.

The high WIC of litter crusts and soil organic matter help to maintain maximum infiltration rates, which allow the penetration of water into soil profile, thereby slowing soil desiccation caused by evaporation (Sayer, 2005). The litter and SOM can increase soil porosity and aeration indirectly, thus increasing the WIR. Our results showed that the SOM content was positively correlated with porosity and negatively correlated with BD. Meanwhile, compared to BSL, the litter crusts increased the WIR under water supplies >1000 mL. The low water supply (500 and 1000 mL) was similar to low-intensity rainfall, and water was quickly absorbed by soil or litter crusts. This observation is believed the amount of water that is wetting-up and the storage within the empty spaces in soil or litter crusts that are not yet at their water retention capacities (Dunkerley, 2015), as a result, there were no significant differences in the WIRs between different crust types. In contrast, a high water supply (> 1000 mL) may result in an enlarged litter percolate flux, which is affected by the rainfall intensity. When the affected soil layer was saturated and water was transported to greater soil layer depths, the WIR could be considered a soil characteristic that is dependent on the initial soil water content (Thompson et al., 2010). Therefore, the TP and SOM contents in the surface soil layer significantly influenced the WIR of low water supplies, and BD and SWC significantly influenced the WIR of high water supply. The increased WHC and WIC in litter crusts and surface soil layers are the main reason the WIR in the litter crusts were slightly lower than BSL. In addition, abundant SOM results in a soil structure that is not compacted, which can lead to the partitioning of water into lateral flows in litter crusts.

More diverse litter crusts can reasonably be assumed to be structurally richer than monospecific litter crusts (Hättenschwiler et al., 2005). Different litter sizes, litter shapes and litter colours all contribute to distinct geometric organization, WIC, WHC and radiative-energy balance in a species-rich litter layer (Sato et al., 2004). In our study, the monoculture litter was researched when analysing the impacts of litter crusts on the soil properties and hydrological functions. In the future, the effects of litter crusts mixed with different species not only on litter structure but also on the movement of water within the litter crusts should be considered. Moreover, the litter crusts affected vegetation properties, such as seed germination, seedling emergence, establishment, and survival (Jia et al., 2018), and this should receive more attention to improve the vegetation in desert ecosystems.

5. Conclusions

Litter crusts significantly influenced the soil properties and hydrological functions. The presence of litter crusts plays a critical role in soil fertility and hydrological functions in sandy lands. Litter crusts increased the soil water content in both the surface (0-5 cm) and subsurface (5-10 cm) soils, but biocrust increased the soil water content in the surface soil and decreased it in the subsurface soil. Litter crusts significantly increased soil organic matter, which was 2.4 times the content in biocrusts and 3.84 times the content in bare sandy lands. Higher organic matter content resulted in increased soil porosity and decreased soil bulk density. Meanwhile, soil organic matter can help to maintain maximum infiltration rates. Litter crusts significantly increased the water infiltration rates under high water supplies (> 1000 mL). The water infiltration rate was mainly determined by soil organic matter and soil porosity under low water supplies. The water infiltration was mainly determined by soil water content and crust properties under high water supplies. Our results suggested that litter crusts significantly improved the soil properties, thereby influencing the hydrological processes. A number of national ecological programmes have improved vegetation recovery and litter crust development extensively in China. The results indicate that litter crusts are instrumental in many hydrological processes because of their ability to increase organic matter and water infiltration. Therefore, it is necessary to consider the hydrological effectiveness of litter crusts. In the future, the effects of litter crusts mixed with different species not only on litter structure but also on the movement of water within the litter crusts should be considered. Moreover, the litter crusts effected vegetation properties, such as seed germination, seedling emergence, establishment, and survival, and these factors should receive more attention to improve the vegetation in desert ecosystems.

Acknowledgements

This research was funded by the National Natural Science Foundation of China (NSFC 41722107, 41525003, 41390463), the West Light Foundation of the Chinese Academy of Science (XAB2015A04), and the Youth Talent Plan Foundation of Northwest A & F University (2452018025).

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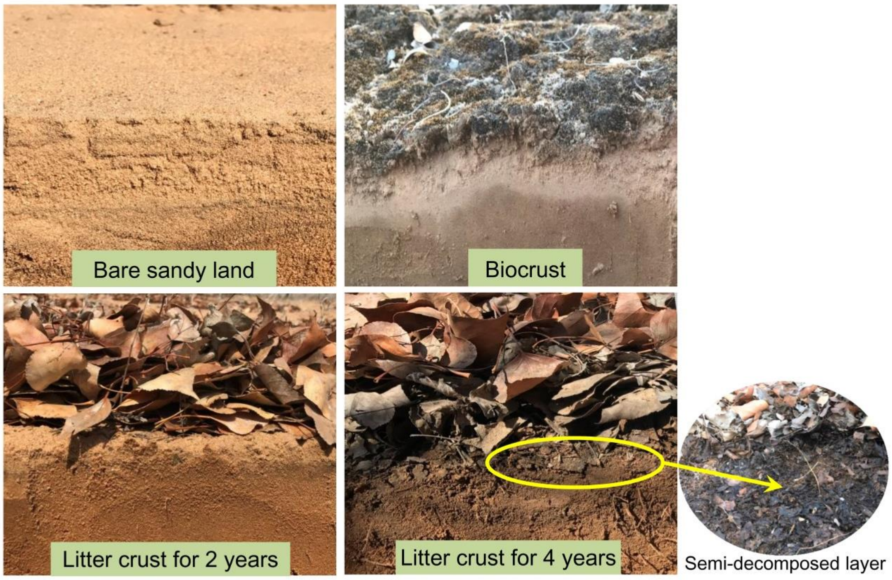
Table 1. Soil water content and bulk density (Mean ± S.E.) at the 0-10 cm soil layer depth under different types of crusts. SWC, soil water content; BD, bulk density; TP, soil total porosity; BSL, bare sandy land; Bio, moss crust; LC2, litter crust for 2 years; LC4, litter crust for 4 years. Different lowercase letters indicate significant differences among the various crust soils at the level of $p < 0.05$.

	Depth (cm)	BSL	Bio	LC2	LC4
SWC (%)	0-5	3.86 ± 0.22b	8.02 ± 1.42a	5.23 ± 0.28ab	7.22 ± 0.60a
	5-10	5.13 ± 0.41a	4.49 ± 0.36a	5.74 ± 0.44a	5.92 ± 0.39a
BD (g cm^{-3})	0-5	1.52 ± 0.01a	1.53 ± 0.02a	1.55 ± 0.02a	1.33 ± 0.04b
	5-10	1.61 ± 0.02a	1.54 ± 0.03ab	1.63 ± 0.01a	1.46 ± 0.03b
TP (%)	0-5	42.73 ± 0.30b	42.30 ± 1.50b	41.43 ± 0.75b	49.85 ± 1.66a
	5-10	39.38 ± 0.74b	42.04 ± 1.08ab	38.64 ± 0.52b	44.82 ± 1.27a

Table 2. Effects of crust types and the amount of water supply on the water infiltration time, infiltration depth and infiltration rate in the study.

	Time		Depth		Rate	
	t	*p*	t	*p*	t	*p*
Type	-6.909	< 0.001	6.697	< 0.001	3.502	< 0.001
Water	20.496	< 0.001	24.918	< 0.001	-4.055	< 0.001

463 

464 **Figure 1.** The vertical soil profiles in different crusts in the study.

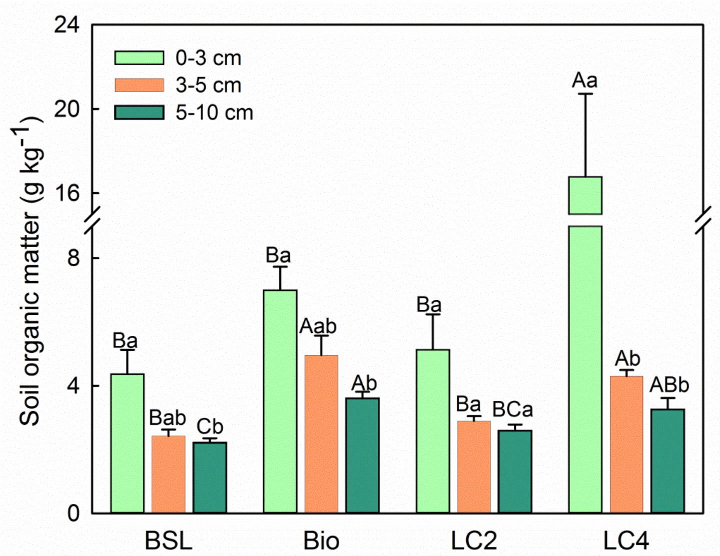


Figure 2. Soil organic matter content (0-10 cm soil depth) in different crust soils. Note: Bio, moss crust; LC2, litter crust for 2 years; LC4, litter crust for 4 years. Different uppercase letters indicate significant differences among the various crust soils in the same soil layer at the level of $p < 0.05$, different lowercase letters indicate significant differences among the different soil layers at the level of $p < 0.05$.

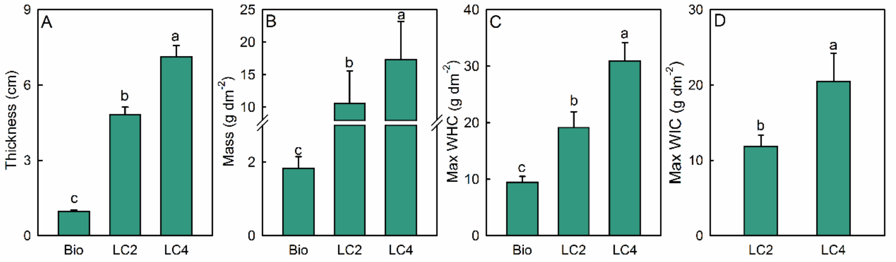


Figure 3. Thickness (A), mass (B), maximum water holding capacity (C) and maximum water holding rate (D) in the different crust plots (M±SE). Note: Bio, moss crust; LC2, litter crust for 2 years; LC4, litter crust for 4 years. Different lowercase letters indicate significant differences among the various crust plots at the level of $p < 0.05$.

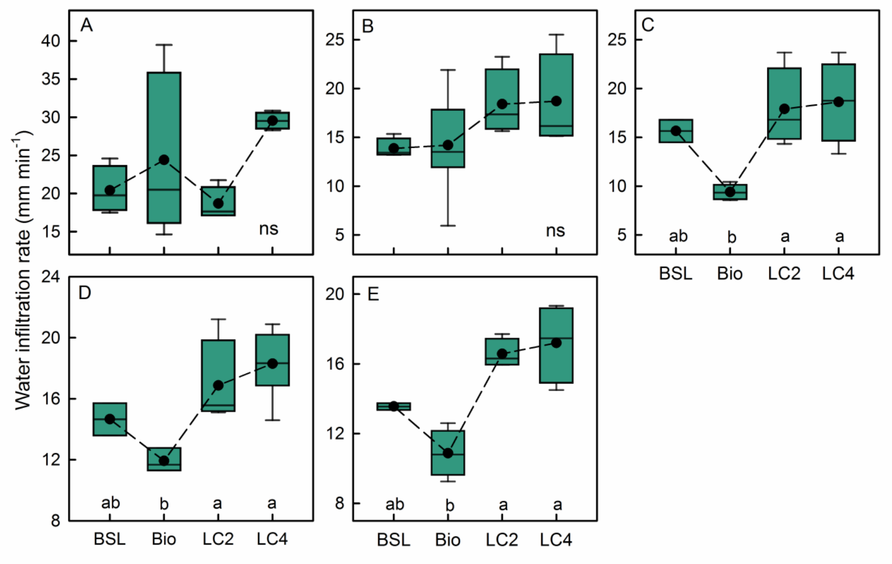
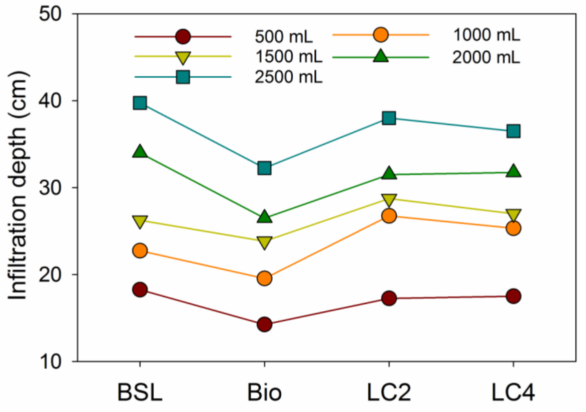


Figure 4. Water infiltration rates (M±SE) of different water supplies (A-500 mL, B-1000 mL, C-1500mL, D-2000 mL, E-2500 mL) among crust types. Note: Bio, moss crust; LC2, litter crust for 2 years; LC4, litter crust for 4 years. Dashed lines represent the average values. Different lowercase letters indicate significant differences among the various crust plots at the level of $p < 0.05$.



485

486 **Figure 5.** Water infiltration depth of different water supplies among crust types. Note: Bio,

487 moss crust; LC2, litter crust for 2 years; LC4, litter crust for 4 years; 500 mL, 1000 mL, 1500

488 mL, 2000 mL, and 2500 mL represent the quantities of water supplied at different treatments.

489

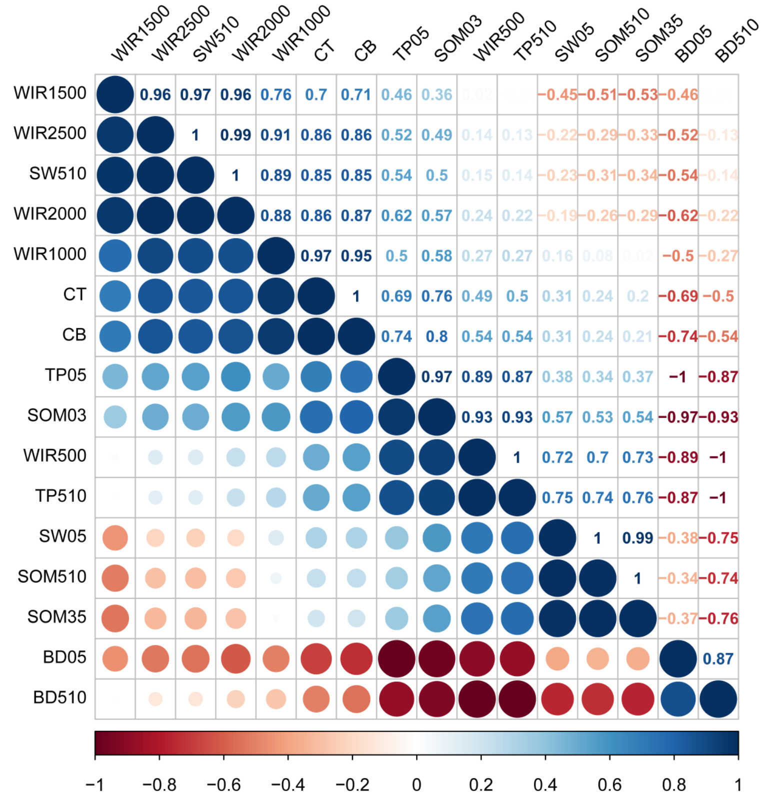


Figure 6. Correlation matrix among the different soil and crust properties and water infiltration rates. Note: blue indicates positive correlations and red indicates negative correlations; the numerical values represent correlation coefficients. WIR500, WIR1000, WIR1500, WIR2000, WIR2500 represent water infiltration rates (mm min^{-1}) of the 500 mL, 1000 mL, 1500 mL, 2000 mL, 2500 mL water supplies, respectively; CT and CB represent crust thickness (cm) and crust mass (g dm^{-2}); SW05 and SW510 represent soil water content in the 0-5 cm and 5-10 cm soil layers (%); SOM03, SOM35 and SOM510 represent soil organic matter content (g kg^{-1}) in the 0-3 cm, 3-5 cm, and 5-10 cm soil layer, respectively; BD05 and BD510 represent soil bulk density (g cm^{-3}) in the 0-5 cm and 5-10 cm soil layers; TP05 and TP510 represent soil total porosity (%) in the 0-5 cm and 5-10 cm soil layers.