Biocrust development and disturbance controls on soil infiltrability in a semiarid ecosystem

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Abstract: The biocrust occurrence and its disturbance alters infiltration in the Mu Us Desert. Knowledge of the hydrological properties of biocrusts and parameterization of soil hydraulic properties are crucial to improve simulation of infiltration and soil water dynamics in vegetation-soil-water models. Infiltration experiment was conducted to evaluate the effects of biocrust development and its disturbance on soil infiltrability in Mu Us Desert, northwest of China. A combined Wooding inverse approach was used for the estimation of soil hydraulic parameters. The results showed that both lichen- and moss-covered biocrusts had a negative influence on infiltration in comparison with the bare soil. Biocrust disturbance alters infiltration, but its effect differs depending on the biocrust and disturbance types. For high pressure heads, water retention on the moss-covered soils was higher than on the lichen-covered soils.

Moreover, trampling caused a higher water retention at high pressure heads. However, opposite was observed at low pressure heads. In addition, moss-covered soils had lower hydraulic conductivity than the lichen-covered soils. Additionally, for each biocrust-covered soil, both trampling and scraping resulted in a higher hydraulic conductivity when compared with the undisturbed soils. The occurrence of biocrusts and its disturbance influenced van Genuchten parameters, and subsequently affected the water retention curve, and thus altered the plant-available water. The findings about the parameterization of soil hydraulic properties are crucial for the simulation of eco-hydrological processes in arid and semiarid ecosystems.

Key words: infiltration; lichen; moss; hydraulic parameter; inverse approach

1. Introduction

Biological soil crusts (also named biocrusts) are generally found in dryland ecosystems around the world (Belnap, 2006; Li et al., 2010; Rodriguez-Caballero et al., 2015; Wang et al., 2017; Weber et al. 2016; Zhao et al., 2011). Biocrusts result from a configuration between soil particles and cyanobacteria, algae, fungi, lichens, and mosses within the upper millimeters of the soil (Eldridge et al., 2010; Bowker et al, 2018). Biocrusts alter physicochemical properties of topsoils and have crucial influence on rainwater infiltration (Belnap et al., 2003; Chamizo et al., 2016; Jiang et al., 2018; Li et al., 2010; Wang et al., 2017; Yu et al., 2010). Nevertheless, contradicting results exist in the roles of biocrusts on soil water infiltration (Warren 2003a; Weber et al. 2016). At a regional scale, different climate regimes cause different types of biocrusts, which could result in the controversial results (Weber et al., 2016). More specifically, a climate gradient that changes from hyper-arid to hotarid and semi-arid or to cool/cold semi-arid increases the roughness and biomass of biocrusts, both of which increases water infiltration (Belnap, 2006; Weber et al., 2016).

Despite their crucial roles in hydrological processes, biocrusts are very fragile and are susceptible to disturbance (Eldridge et al., 2011; Faist et al., 2017). Trampling is a common disturbance in these ecosystems due to livestock grazing or vehicular traffic. The disturbance can lead to partial or complete destruction of the biocrusts, increasing water infiltration (Bowker et al., 2011). However, these compressional forces from the disturbance may compact soil, and thus decrease water infiltration (Chamizo et al., 2012). Therefore, the effect of the biocrust disturbance on water infiltration was unclear. In addition, the influence of the biocrust disturbance on water infiltration can be highly dependent on the stages of biocrust development (Chamizo et al., 2012; Belnap, 2006).

However, the influence of biocrusts and its disturbance on water infiltration have not been sufficiently evaluated. The type or level of disturbance influences the effect of biocrusts on hydrological functions, and this effect is dependent upon biocrust type or developmental stage (Belnap and Eldridge, 2003). In semi-arid areas with high roughness of biocrusts, disturbance could suppress infiltration by destroying the structure of biocrusts and compacting the soil, and thereby advancing the development of physical soil crusts (Chamizo et al., 2012; Herrick et al., 2010). On the contrary, in the hyperarid and arid areas with smooth biocrusts, disturbance could facilitate infiltration by destroying these smooth or hydrophobic surfaces (Bowker et al., 2013). Given that the soil and biocrust types differ in different areas, further studies will be needed to test these research results in other areas, such as the Mu Us Desert.

In addition, the presence of biocrusts and its disturbance alters soil physical properties, and subsequently influences soil hydrological processes, and thus changes plant-available water. Improved knowledge of the hydrological properties of biocrusts and estimation of soil hydraulic parameters are crucial to improve simulation of infiltration and soil water dynamics in vegetation-soil-water models, and have important implications for the simulation of eco-hydrological processes in dryland ecosystems.

We hypothesized that the type of disturbance would affect the degree to which biocrust development alters infiltration. Accordingly, the purposes of our study were to: (1) evaluate whether biocrust developmental stage influence soil water infiltration; (2) explore whether disturbance influence the degree to which biocrusts affect soil water infiltration; (3) estimate the hydraulic parameters in the disturbed and undisturbed biocrust-covered soils.

2. Materials and methods

2.1. Experimental site

This study was undertaken at the Yanchi Research Station, Ningxia Province, northwestern China (106°30′−107°47′ E and 37°04′−38°10′ N, 1550 m above the sea level). The site is located on the southwestern fringe of the Mu Us Desert and is characterized by a mid-temperate semi-arid climate with mean annual temperature of 8.1 °C. Mean annual precipitation in this area is 287 mm, most of which occurs from July to September. Soil texture is classified as sand. The dominant shrubs are *Artemisia ordosica*, *Caragana korshinskii*, *Salix psammophila* and *Hedysarum mongolicum*, which are distributed in patches covering 30–70% of the soil surface. The soil surface of inter-canopy is usually covered by biocrusts.

There exist a successional gradient in this area, which change from the early (i.e., lichens) to late-successional stages (i.e., mosses). The lichen-dominated biocrusts are mainly composed of *Collema tenax* species of lichens with a little bit of algae cover. The moss-dominated biocrusts, in addition to *Byumargenteum* species of mosses, include a certain amount of lichens. A vernier caliper and line intercept transects were used for measuring the thickness and cover of biocrusts, respectively. Biocrust samples, which were manually screened through a 2-mm screen and dried at 65 °C for 24 h, were used for measuring the biomass.

2.2. Experimental design

In this study, infiltration experiments were conducted in July 2016 to explore the influence of biocrusts and its disturbance on water infiltration. In the experiment, two biocrust types, which included lichen- and moss-dominated biocrusts, were considered. Each soil biocrust type subjected to three disturbance treatments: undisturbed, trampled, and scraped. Three replicates were obtained for each treatment and the average values were used for data analysis.

2.3. Infiltration Measurements

The infiltration measurement was undertaken with a disc infiltrometer under pressure heads (h) of -3, -6, and -12 cm at each infiltration point. The infiltrometer was 15 cm in diameter. The diameter and height of the water reservoir tower was 3.5 and 100 cm, respectively. Prior to each measurement, a layer of fine sand with thickness of 2 mm was laid on soil surface at each infiltration point and then the disc infiltrometer was put on the fine sand. The water level of in the reservoir tower was recorded until it reached steady state. The time interval for observation was 10 s during the first 3 min of the infiltration experiment. However, the time interval for observation was 30 s when the infiltration time reached 3 min.

2.4. Calculation of soil hydraulic parameters

The following method was adopted to analyze the infiltration data. At long time, the infiltration from a circular source with a constant pressure head could be described by the Wooding's solution (Wooding, 1968):

$$Q=\pi r_0^2 K(h)[1+\frac{4\lambda_c}{\pi r_0}] \tag{1}$$

with λ_c is expressed as (White and Sully, 1987):

$$\lambda_c = bS^2/[K(h)(\theta_0-\theta_{ini})] \tag{2}$$

where Q is the steady-state infiltration rate (cm^3 min^{-1}); r_0 is the radius of the disc (cm); $K(h)$ is the unsaturated conductivity under a given pressure head (cm min^{-1}); h is the pressure head (cm), which was -3, -6, and -12 cm; λ_c is the macroscopic capillary length; b is a shape parameter between 1/2 and π/4 (Smettem and Clothier, 1989); S is the sorptivity (cm min$^{-1/2}$); θ_0 is the final soil water content (cm^3 cm^{-3}); and

θ_{ini} is the initial surface soil water content ($\text{cm}^3\ \text{cm}^{-3}$).

The Q can be calculated as the following form by substituting Equation (2) into (1):

$$Q/(\pi r_0^{\,2}) = K(h) + 4bS^2/[\pi r_0(\theta_0 - \theta_{ini})] \tag{3}$$

with i_c is expressed as:

$$i_c = Q/(\pi r_0^{\,2}) \tag{4}$$

From Equations (3) and (4), the $K(h)$ can be calculated as the following form by replacing Q with constant infiltration rate (i_c, cm min^{-1}) (White and Sully, 1987):

$$K(h) = i_c - 4bS^2/[\pi r_0(\theta_0 - \theta_{ini})] \tag{5}$$

In this equation, S was estimated by the intercept of the regression line between $\Delta I/\Delta t^{1/2}$ and $t^{1/2}$ according to Vandervaere et al. (1997), where ΔI is the variable quantity of cumulative infiltration (cm) and $\Delta t^{1/2}$ is the variable quantity of the square root of time (min); i_c was calculated by the slope of the linear fitted cumulative infiltration curves with the stable infiltration data.

According to the quasi-linear Gardner model (Gardner, 1958), the $K(h)$ (cm min^{-1}) could be expressed as:

$$K(h) = K_s \exp(\alpha_{GRD} h) \tag{6}$$

Where α_{GRD} is the exponential slope; K_s is the saturated hydraulic conductivity (cm min^{-1}).

From Equations (5) and (6), the K_s could be expressed as:

$$K_s \exp(\alpha_{GRD} h) = i_c - 4bS^2/[\pi r_0(\theta_0 - \theta_{ini})] \tag{7}$$

The K_s and α_{GRD} in Equation (7) are only the two unknown parameters, which could be calculated by two consecutive pressure heads. The approach assumes that parameter α_{GRD} is constant over the interval between two consecutive pressure heads (Coppola et al., 2011).

The microscopic pore radius (λ_m, mm) was calculated through Equations (8) according to White and Sully (1987).

$$\lambda_m = \frac{\sigma \alpha_{GRD}}{\rho g} \tag{8}$$

where g is the acceleration due to gravity (N kg^{-1}), ρ is the density of water (kg m^{-1}), σ is the surface tension (N m^{-1}).

2.5. Estimation of van Genuchten parameters using a combined Wooding inverse approach

A coupled Wooding inverse approach that combined the results from Wooding's analytical solution with a parameter estimation method using a numerical solution of the Richards equation, was used to estimate van Genuchten parameters (Coppola et al., 2011; Lazarowitch et al., 2007).

The following form of the Richards equation is usually used to characterize the radially symmetric isothermal Darcian flow in a variably saturated isotropic rigid porous medium (Warrick, 1992):

$$\frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z} - 1\right) \tag{9}$$

where z is the vertical coordinate positive downward, r is the radial coordinate, and t is time. Initial and boundary conditions that are appropriate for a disc tension infiltrometer experiment are expressed by the following equations (Šimůnek and van Genuchten, 2000):

$$h(r,z,t)=h_0(t)\quad 0<r<r_0, z=0 \tag{10}$$

$$\frac{\partial h(r,z,t)}{\partial z}=1\quad r>r_0, z=0 \tag{11}$$

$$h(r,z,t)=h_{ini}\quad r^2+z^2\rightarrow\infty \tag{12}$$

$$h(r,z,t)=h_{ini}(z)\quad t=0 \tag{13}$$

where r_0 is the disc radius (cm), h_0 is the time-variable supply pressure head (cm), and h_{ini} is the initial pressure head (cm).

The van Genuchten model (van Genuchten, 1980) was chosen to express the soil water retention, $\theta(h)$, and hydraulic conductivity, $K(\theta)$:

$$S_e=\frac{\theta-\theta_r}{\theta_s-\theta_r}=[1+|\alpha_{VG}h|^n]^{-m}\quad m=\frac{n-1}{n} \tag{14}$$

$$K(S¿¿e)=K_s S_e^l[1-(1-S_e^{1/m})^m]^2 ¿ \tag{15}$$

where θ_r and θ_s are the residual and saturated soil moisture (cm^3 cm^{-3}), respectively, α_{VG} (cm^{-1}), m and n are the shape parameters, S_e is the effective fluid saturation, and l is the tortuosity parameter, which was usually fixed at 0.5 (Mualem, 1976).

The transient tension disc infiltration data, together with initial and final soil moisture, were used for the numerical inverse determination of van Genuchten parameters, by fixing K_s at the value obtained using Wooding's analytical solution. The objective function, Φ, for the numerical inverse approach is:

$$\Phi(\beta)=\sum_{i=1}^{M} W_i\left[I_i^{*}(t_i)-I(\beta,t_i)\right]^2 \tag{16}$$

where M is the number of measurements in a particular set, β is the vector of optimized parameters; W_i is the weight of a particular measured point, I_i^* (cm) is the measured cumulative infiltration at time t_i, and I_i (cm) is the simulated cumulative infiltration at time t_i.

2.6. Data analyses

A three-way ANOVA was used for analyzing the effects of biocrust type and its disturbance on the soil water infiltrability at the 5% probability level. The differences in soil hydraulic parameters among these treatments were analyzed using the least significant difference (LSD) tests at the 5% probability level. All statistical analyses were performed using the SPSS 19.0 software (SPSS, Chicago, IL, USA).

3. Results

3.1. Characteristics of biocrusts

The characteristics of biocrusts is shown in Table 1. The cover, thickness, polysaccharide content, and fine content (clay and silt) of lichen-dominated biocrusts were lower than moss-dominated biocrusts. In contrast, lichen-dominated biocrusts had slightly higher soil bulk density than moss-dominated biocrusts (Table 1).

3.2. Effects of biocrust type on infiltration

As shown in Fig. 2, from initial to steady state, lichen-dominated biocrusts had much higher infiltration rates than moss-dominated biocrusts. For example, for the undisturbed treatment, the i_{ini} and i_{c} averaged over the three pressure heads of lichen-dominated biocrusts were higher than moss-dominated biocrusts by 1.9 and 7.6-fold, respectively (Table 2). In addition, the S and $K(h)$ of lichen-dominated biocrusts were significantly higher than moss-dominated biocrusts (Table 2). Specifically, for the undisturbed treatment, the S and $K(h)$ averaged over the three pressure heads of lichen-covered treatments were significantly higher than moss-covered treatments by 1.8- and 7.7-fold, respectively.

The results of three-way ANOVA revealed that the influences of biocrust type on i_{ini}, i_c, S, and $K(h)$ were significant at the 0.01 level, whereas the influences of biocrust type on λ_c and λ_m were insignificant at the 0.05 level. In addition, the influences of the interaction between the biocrust type and disturbance on i_c, S, and $K(h)$ were significant at the 0.01 or 0.05 level (Table 3).

3.3. Effects of disturbance on infiltration

As shown in Fig. 2, for either lichen- or moss-dominated biocrusts, scraping and trampling remarkably increased infiltration rates. This effect was more pronounced for the scraped treatment than the trampled treatment. In detail, as shown in Table 2, the scraped treatment had significantly higher i_{ini} and i_c than the undisturbed treatment. Similarly, compared to the undisturbed soil, trampling resulted in higher i_{ini} and i_c, although there was no significant difference except for the lichen-covered treatment under the pressure head of -3 cm. Furthermore, the i_{ini} and i_c in the scraped treatment were higher than the trampled treatment, although there was no significant difference for the most treatments.

In addition, S in the trampled and scraped treatments were higher than the undisturbed treatment, although there was also no significant difference except for the lichen-covered treatment under the pressure head of -3 cm. However, similar phenomenon was not observed in the moss-covered treatments. Although the scraped treatment had obviously higher S than the undisturbed treatment, there was no obvious difference between the trampled and undisturbed treatments (Table 2).

$K(h)$ followed the pattern scraped > trampled > undisturbed. For example, for lichen-covered soils, the $K(h)$ averaged over the three pressure heads for the scraped and trampled treatments were 75.1% and 22.9% higher than the undisturbed treatment, respectively (Table 2). In addition, the influence of disturbance on $K(h)$ was dependent on the biocrust type. In detail, for moss-covered soils, the difference was insignificant among the three disturbance treatments, whereas the scraped treatment had significantly higher $K(h)$ than the undisturbed treatment for the lichen-covered soils ($P < 0.05$).

There was no simple positive or negative effect of disturbance on the λ_c. The effect of disturbance on the λ_c was dependent on biocrust type. Specifically, for the lichen-dominated biocrusts, the λ_c in the scraped and trampled treatments were higher than that in the undisturbed treatment; however, similar pattern was not observed for the moss-dominated biocrusts. In addition, opposite pattern was observed in the λ_m (Table 2). The three-way ANOVA results showed that the effect of disturbance on i_{ini}, i_c, S, and $K(h)$ were significant at the 0.01 level. Moreover, the interactive effects of biocrust type and disturbance on i_c, S, and $K(h)$ was also significant at the 0.01 or 0.05 level (Table 3).

3.4. Determination of van Genuchten parameters

As shown in Table 4, for the lichen-covered treatments, the K_s averaged over all the three disturbance treatments was higher than that for the moss-covered treatments by 2.0-fold. Furthermore, disturbed treatments had higher K_s than the undisturbed treatment. The two-way ANOVA results indicated that the effects of biocrust type and its disturbance and their interactive effects on K_s were insignificant at the 0.05 level (Table 4).

As shown in Table 4, the θ_s and α_{VG} for the moss-covered treatments were slightly higher than that for lichen-covered treatments, whereas the lichen-covered treatments had higher n than the moss-covered treatments. Additionally, the influence of disturbance on the θ_s, α_{VG} and n was dependent on disturbance type. In detail, for lichen-covered soils, the trampled treatment had higher θ_s and α_{VG} as compared to the undisturbed treatment, whereas opposite pattern was observed in the scraped treatment. Moreover, for the lichen-covered treatments, both the trampled and scraped treatments had higher n than the undisturbed treatment. Similarly, for the moss-covered soils, the θ_s and α_{VG} for the trampled treatments were higher than the undisturbed treatment, although there was no significant difference. For the moss-covered soils, the scraped treatment had slightly lower θ_s than the undisturbed treatment. Furthermore, for the moss-covered treatments, both the trampled and scraped treatments had lower n than the undisturbed treatment. The results of two-way ANOVA showed that the influences of biocrust type on θ_s, α_{VG} and n were significant at the 0.01 or 0.05 level, while the influences of the disturbance on θ_s, α_{VG} and n were insignificant at the 0.05 level. In addition, the influences of their interaction on θ_s, α_{VG} and n were also insignificant at the 0.05 level (Table 4).

The hydraulic conductivity and water retention curves are illustrated in Fig. 3. For high pressure heads, as shown in Fig. 3a, water retention for the moss-covered treatments were higher than that for the lichen-covered treatments. In addition, the trampled treatment had higher water retention than that for the undisturbed treatment at high pressure heads, and scraping caused a reduction in water retention. However, opposite was observed at low pressure heads.

As shown in Fig. 3c, moss-covered treatments had lower $K(h)$ than the lichen-covered treatments. Additionally, for each biocrust-covered soil, both the trampled and scraped treatments had higher $K(h)$ than the undisturbed treatment. Moreover, for the moss-covered soils, the scraped treatment resulted in a higher $K(h)$ than the trampled treatment, whereas opposite pattern was observed for the lichen-covered soils.

In addition, the development of biocrusts and its disturbance influences the water retention curve, and thus alters the plant available water (defined as the difference in soil moisture ($\Delta\theta$) within a pressure head ranged from -1 to -1000 cm) (Wang et al., 2007). For example, the available water increased from $\Delta\theta$ = 0.226 m^3 m^{-3} for the undisturbed lichens, to $\Delta\theta$ = 0.235 m^3 m^{-3} for the undisturbed moss. Moreover, for lichen biocrusts, the available water increased from $\Delta\theta$ = 0.226 m^3 m^{-3} for the undisturbed treatment, to $\Delta\theta$ = 0.262 m^3 m^{-3} for the trampled treatment. On the contrary, the available water decreased from $\Delta\theta$ = 0.226 m^3 m^{-3} for the undisturbed treatment, to $\Delta\theta = 0.209$ m^3 m^{-3} for the scraped treatment.

4. Discussion

4.1. Influence of biocrusts on infiltration

This study indicates that both moss- and lichen-dominated biocrusts had a negative influence on infiltration when compared to the bare soil (i.e. scraped treatment) (Table 2). The biocrust effects could be ascribed to the higher amount of clay and silt in biocrusted soils, which block soil pores and lead to a decrease in infiltration (Table 1). Furthermore, reductions in infiltration in biocrusted soils may be due in part to higher polysaccharide content (Table 1) (Colica et al., 2014). The result was coincided with the most studies, which reported that the moss- and lichen-dominated biocrusts caused a decrease in infiltration (Coppola et al., 2011; Eldridge et al., 2000; Liu et al., 2016; Xiao et al., 2019; Yang et al., 2016). For example, Xiao et al. (2019) found that infiltration rates for the moss-dominated biocrusts were significantly lower than the bare sand. Nevertheless, some studies have shown the opposite: the presence of lichen- or moss-dominated biocrusts on soils increased infiltration (Jiang et al., 2018; Xiao et al., 2011). Some scholars argue that the controversy could be partly explained by the difference in soil texture (Warren et al., 2003a). Specifically, sandy soils (i.e., sand content more than 80%) are generally characterized by large pores and rapid infiltration, and the presence of biocrusts can lead to pore clogging, and therefore result in a reduction of infiltration. However, on fine-textured soils (i.e., the combined silt and clay content exceed 20%), biocrusts are thought to increase infiltration, as pore formation by biocrusts has a larger impact on infiltration than pore blocking by them (Warren et al., 2003a; Chamizo et al., 2012). In this study, sand content more than 80%, which caused a negative effect of biocrusts on infiltration.

In addition, we found that moss-covered biocrusts had much lower soil infiltrability compared to the lichen-covered biocrusts (Table 2). Compared with lichen-covered biocrusts, higher thickness, biomass, organic matter content, and polysaccharide content for the moss-covered biocrusts can explain this finding (Table 1) (Colica et al., 2014). Moreover, higher fine content in the moss-covered biocrusts decreased soil infiltrability as compared with the lichen-covered biocrusts (Table 1). This result suggests that biocrust development (from lichens to moss) decrease soil infiltrability, and thus could influence the soil water availability, and may partly explain the degradation of vascular vegetation in this semi-arid region (Guan and Liu, 2019). Similarly, Wu et al. (2012) reported that infiltration decreased with greater biocrust development in temperate environment. In contrast, in both hot and cool semi-arid environments, most studies have shown that infiltration increased with biocrust development, which is characterized by increased biomass (Barger et al. 2006; Belnap et al. 2013; Chamizo et al. 2012). The different response of infiltration to biocrust development was dependent upon climate. Compared with the cool and hot semiarid regions, greater pore clogging and water-holding capacity and finer soil texture in the well-developed biocrusts than those in the early-developed biocrusts in the temperate region could explain the contradictory findings (Weber et al., 2016).

4.2. Influence of biocrust disturbance on infiltration

Given biocrusts are vulnerable to disturbances including trampling, livestock grazing and recreational activities, in addition to analyzing the influence of different types of biocrusts on infiltration, another study was conducted to explore how disturbance affects the response of infiltration to biocrusts. This study demonstrates that biocrust disturbance alters infiltration, but its effect differs depending on the biocrust type and the type of disturbance applied. Specifically, trampling resulted in a reduction in infiltration. In general, sandy soils are characterized by large pores and rapid, and the occurrence of biocrusts may impede infiltration. Trampling tend to cause a disruption of hydrological barrier caused by biocrusts, which could explain the positive effect of disturbance in this study. Previous studies have also reported that trampling increased infiltration (Bowker et al., 2013; Belnap and Eldridge, 2003; Chung et al., 2019; Faist et al., 2017; Kidron, 2016; Zaady et al., 2013) (Table 5). On the contrary, some authors found that trampling resulted in decreased infiltration (Barger et al., 2006; Chamizo et al., 2012; Herrick, 2010). There are two reasons may explain the contradictory findings. Firstly, this could be attributed to the difference in disturbance intensity. In this study, light trampling was designed to disrupt biocrusts without affecting the underlying vesicular layer. However, in other studies, heavily trampling or tracked vehicle traffic could compacts the soil aggregates into an impermeable layer, especially after rainfall, and therefore decreasing infiltration (Chamizo et al., 2012; Zaady et al., 2013). Secondly, the difference in soil type may partly explain this discrepancy. Contrary to sandy soils, the fine-textured soils are prone to clog the narrow soil pores under disturbance conditions, especially after rainfall (Warren, 2003b).

Additionally, we found that the removal of the biocrusts by scraping significantly increased infiltration. Prior studies also reported that scraping enhances infiltration (Cantón et al., 2020; Chamizo et al., 2012; Coppola et al., 2011; Faist et al., 2017; Eldridge et al., 2000) (Table 5). Contrary to the above findings, some authors found that scraped biocrusts reduced infiltration or increased runoff (Chamizo et al., 2012; Zaady et al., 2013). This phenomenon could be due to the difference in soil and biocrust types. In the studies of Zaady et al. (2013), a higher fine content and thus increasing possibility of clogging acts to reduce water infiltration when soil is wet. In addition, Chamizo et al. (2012) found that scalping resulted in increased infiltration in all biocrust types expect in the lichen- and moss-dominated biocrusts on coarse-textured soil. In this study, the effect of disturbance on infiltration was evaluated under dry condition. However, soil infiltrability will change, especially when soil is wet. Additionally, on fine-textured soils, the progressive sealing of the soil (i.e., physical crusts) may arise after raindrop impact, and thus reducing infiltration. Therefore, further studies about the effects of disturbance on the variation of soil infiltrability will be needed, especially after rainfall.

4.3. Determination of van Genuchten parameters

Parametrization of hydraulic properties on biocrust-covered soils is crucial to improve simulation of infiltration and soil water movement in vegetation-soil-water models, and thus understanding eco-hydrological processes in dryland ecosystems (Rodríguez-Caballero et al., 2015). Among them, the most important work is to estimate the parameters of van Genuchten model. In our study, the results showed that lichen-covered soils had higher K_s than moss-covered soils; however, the θ_s for the lichen-covered soils was lower than that for moss-covered soils, although the differences were insignificant. This result can also be explained by higher fine content (i.e., fine and clay) and polysaccharide content on moss-covered soils when compared to lichen-covered soils (Table 1). Moreover, coinciding with this simulation study, the results of field experiments of Guan and Liu (2019) also reported that well-developed moss biocruts had higher θ_s than lichen biocrusts, suggesting a higher retention capacity for the moss biocrusts.

In addition, the results showed that the α_{VG} and n for the lichen-covered soils were slightly lower than that for moss-covered soils under undisturbed soil conditions. This result suggests that the shape parameters (α_{VG} and n) increased with biocrust development. Moreover, this result indicates that the higher α_{VG} and n were consistent with a higher content of clay and silt. In contrast, Wang et al. (2007) found that the shape parameters (α_{VG} and n) decreased with increased time since stabilization, and the lower α_{VG} and n were related to a higher proportion of silt- and clay-sized particle. The difference in the inverse method and model uncertainty may explained this contradiction.

In our study, both trampling and scraping reduced K_s on either lichen-covered or moss-covered soils. This result suggests that light disturbance of biocrusts can replenish the water in the root layer of the soil. Furthermore, the effect of disturbance on θ_s was dependent on disturbance type. In detail, trampling increased θ_s, while scraping reduced θ_s. In addition, the influence of disturbance on the θ_s, α_{VG} and n was dependent on biocrust and disturbance types.

The different van Genuchten parameters influence the $\theta(h)$ and $K(h)$ curves. The results showed that for high pressure heads, $\theta(h)$ on the moss-covered soils was higher than on the lichen-covered soils (Fig. 3a and b). Moreover, compared to the undisturbed soils, trampling caused a higher $\theta(h)$ at high pressure heads. However, opposite was observed at low pressure heads (Fig. 3a and b). In addition, moss-covered soils had lower $K(h)$ than the lichen-covered soils. Additionally, for each biocrust-covered soil, both trampling and scraping resulted in a higher $K(h)$ when compared with the undisturbed soils. Increase in $\theta(h)$ and decrease in $K(h)$ can be ascribed to the peculiarity of biocrusts when compared to bare sand. As pointed out by Belnap (2006), the anchoring structures on lichen-covered soils can bind soil particles and lead to the formation of mats, which enhance water retention at the soil surface. Furthermore, higher content of clay and silt in moss-covered biocrusts block soil pores, and cause a decrease in soil hydraulic conductivity. Therefore, the formation of lichen- or moss-dominated biocrusts enhances water retention, whereas soil hydraulic conductivity can be restricted.

The occurrence of biocrusts and its disturbance influences van Genuchten parameters, subsequently affects the water retention curve, and thus alters the plant-available water. Our results showed that biocrust development increased the plant-available water. Furthermore, trampling increased the plant-available water, while scraping resulted in a reduction of the plant-available water. It is noted that the plant-available water mentioned above focused on the soil surface. The increased water content on the soil surface implies a lower soil water content of the shrub root layer. Our study focused on the effects of biocrusts and its disturbance on soil infiltrability. However, how the biocrust development and its disturbance influence soil water availability and vascular vegetation growth is unclear (Kidron and Aloni, 2018). Therefore, further studies will be needed to explore the effects of the biocrust development and its disturbance on soil water availability and growth of artificially planted shrubs.

5. Conclusions

The effects of biocrust development and its disturbance on soil infiltrability and van Genuchten parameters were evaluated. Our results showed that both lichen- and moss-covered biocrusts had a negative influence on infiltration in comparison with the bare soil. Moreover, biocrust development (from lichens to mosses) decrease soil infiltrability. Biocrust disturbance alters infiltration, but its effect differs depending on the biocrust type and the type of disturbance applied. The occurrence of biocrusts and its disturbance influences van Genuchten parameters, subsequently affects the water retention curve, and thereby alters the plant-available water. The findings about the parameterization of soil hydraulic properties have important implications for the simulation of eco-hydrological processes in dryland ecosystems.

Acknowledgements

This study was funded by the Fundamental Research Funds for the Central Universities (BLX2013030 and 2015ZCQ-SB-02).

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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