

Effects of biocrusts and rainfall characteristics on runoff generation in the Mu Us Desert, northwest China

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ABSTRACT

How the presence of biocrusts regulates runoff generation in the Mu Us Desert is not well known. Runoff experiments under natural and artificial rainfalls and numerical simulations were conducted in semiarid environments to evaluate the effects of biocrust type and rainfall characteristics on runoff. The experimental results showed that the water drop penetration time (WDPT) of the moss-dominated biocrusts was 68.7% higher than that of lichen-dominated biocrusts. Nevertheless, the saturated hydraulic conductivity (K_s) for moss-dominated biocrusts was 72.7% lower than that for the lichen-dominated biocrusts. Runoff yield for moss-dominated biocrusts was significantly higher than that for lichen-dominated biocrusts. Runoff yield was mainly explained by rainfall amount (or maximum 5-min rainfall intensity, $I_{5\max}$) ($P < 0.001$) and WDPT ($P = 0.001$). The influences of biocrust type, rainfall intensity, and their interaction on runoff coefficient were significant at the probability level of 0.01. The results of numerical simulations concluded that surface runoff was generated for lichen- and moss-dominated biocrusts when rainfall intensity reached 73.5 and 49 mm h⁻¹, respectively. Runoff coefficient in the moss-covered soil increased obviously when rainfall intensity changed from 49 to 73.5 mm h⁻¹. The results suggest that runoff could be changed substantially under increasing trends in rainfall intensity in the Mu Us Desert.

Key words | HYDRUS-1D, lichen, moss, rainfall amount, rainfall intensity, surface runoff

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INTRODUCTION

Soil moisture availability is the most important factor affecting plant growth. The availability of water for plant uptake is affected by the processes that determine the division of rainfall into infiltration and surface runoff (Wang *et al.* 2016). The division of rainfall into surface runoff and infiltration is especially important in arid and semiarid regions (Chen *et al.* 2013). Runoff can change soil water distribution, providing water for vegetation at sites downslope (Thompson *et al.* 2010). In these regions, Hortonian overland flow occurs when the rate of rainfall exceeds the soil water infiltration of the upper soil (Van de Giesen *et al.* 2011; Kidron 2015). The overland flow, as a vital component of the hydrological processes, is usually shaped by both soil surface attributes and rainfall characteristics.

Among soil surface attributes affecting soil hydrology in drylands, biological soil crusts (referred to as biocrusts) are usually found in arid and semiarid regions, which comprise up to 40% of the Earth's terrestrial surface (Belnap & Lange 2003; Reynolds *et al.* 2007; Xiao *et al.* 2014; Weber *et al.* 2016). Biocrusts change the physicochemical properties of the soil surface, which could result in runoff generation (Chamizo *et al.* 2012a). Biocrusts, in particular lichens and mosses, supply the soil with good protection from raindrop erosion (Belnap 2006). Biocrusts on the soil surface have substantial impacts on local hydrological processes, such as soil water infiltration (Rodríguez-Caballero *et al.* 2015b), runoff (Belnap 2006), and evaporation (Chamizo *et al.* 2013). However, publications on the effects of biocrusts on

infiltration or runoff have reported conflicting results (Warren 2003; Weber *et al.* 2016). Some rainfall simulation experiments in both hot and cool semiarid regions found that soil water infiltration increased with biocrust development (Li *et al.* 2002a; Barger *et al.* 2006; Xiao *et al.* 2011; Chamizo *et al.* 2012a; Belnap *et al.* 2013). On the contrary, some studies showed that infiltration decreased with greater biocrust biomass (Li *et al.* 2010; Wu *et al.* 2012; Zhao & Xu 2013). In temperate regions, several studies showed that biocrusts have a substantial impact on local hydrological properties. Drahorad *et al.* (2013), Fischer *et al.* (2013), and Lichner *et al.* (2012) all found that water repellency increased and the saturated hydraulic conductivity decreased with biocrust development. Since the biocrust and soil types vary in different research areas, further field experiments are necessary to verify these research results in other regions, such as the Mu Us Desert.

The hydrological behavior of biocrusts depends on rainfall characteristics (e.g. intensity and amount) as documented by Kidron *et al.* (2012) and Rodríguez-Caballero *et al.* (2013). First, the interaction of biocrusts and rainfall intensity influences infiltration or runoff. In fact, well-developed biocrusts reduce runoff if compared to bare land for low-intensity rainfall events (Rodríguez-Caballero *et al.* 2013). However, during high-intensity rainfall events, well-developed biocrusts showed higher runoff than bare land (Chamizo *et al.* 2012a, 2012b). Second, rainfall amount can also change the influence of biocrusts on infiltration or runoff. In drylands, rainfall typically occurs in large amounts which leads to saturation of biocrusts (e.g. Kidron & Yair 1997). Additionally, in the Tengger Desert, biocrust cover had a substantial negative effect on the soil water infiltration for low rainfall amounts, whereas the opposite occurred with large rainfall amounts (Wang *et al.* 2007). In addition, some studies explored the influence of rainfall amount on the relationship between the biocrust development and runoff (Li *et al.* 2010; Wu *et al.* 2012). In China, most studies about the effects of biocrusts on runoff were conducted in the Loess Plateau or Tengger Desert (Li *et al.* 2002b; Xiao *et al.* 2015). Nevertheless, few studies about the effects of rainfall intensity on the relationship between biocrust development and runoff were reported in the Mu Us Desert. Some studies on these aspects were conducted at Jingbian research site, located in the Mu Us Desert, where the

annual average rainfall is 495 mm (Wu *et al.* 2012). Since the biocrust type and rainfall characteristics vary in different rainfall zones, further field experiments are necessary to verify these research results in other regions, such as the Mu Us Desert. Moreover, according to the IPCC (2013), the increasing trends in intensity and frequency of heavy rainfall in drylands were reported. According to the studies of Rodríguez-Caballero *et al.* (2015b), runoff rates are determined by the duration of short intense rainfall. Accordingly, it is important to study the influence of increasing trends in intensity of heavy rainfall on the hydrological response of biocrusts.

We hypothesized that rainfall amount and intensity have a substantial influence on the relationship between biocrust type and runoff. Therefore, the aim of this paper was to: (i) explore whether factors such as water repellency and saturated hydraulic conductivity of different biocrust type affect runoff; (ii) determine whether the interaction of rainfall characteristics (e.g. intensity and amount) and biocrust type affect runoff; (iii) determine the rainfall intensity threshold for generating runoff under different biocrust types and slope gradients.

MATERIALS AND METHODS

Experimental site

The experiments were conducted at the Yanchi Research Station (106°30'–107°41'E, 37°04'–38°10'N, 1,540 m a.s.l.), which is located at the southwestern edge of the Mu Us Desert, Ningxia Autonomous Region, northwest China (Figure 1). The site has a mean annual precipitation of 292 mm, about 62% of which occurs from June to September. The average annual potential evapotranspiration and temperature are 2,024 mm and 8.1 °C, respectively (Guan & Liu 2019). Six replicate measurements of soil properties were conducted. According to the US Soil Taxonomy, soil type is characterized by quartisamment (Gao *et al.* 2014). The average sand, silt, and clay content in the shallow soil profile (0–10 cm depth) were 75.2, 22.3 and 2.5%, respectively. The mean percentages of sand, silt and clay in lower soil (10–60 cm depth) were 93.0, 4.3 and 2.7%, respectively. The soil bulk density and organic carbon content were

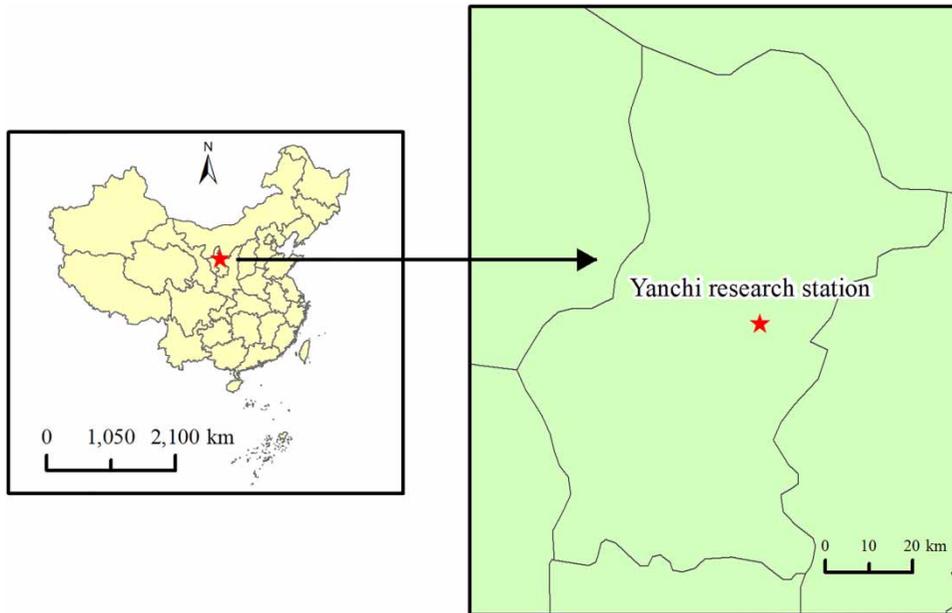


Figure 1 | Location of the study area.

$1.61 \pm 0.35 \text{ g cm}^{-3}$ and $1.7 \pm 0.1 \text{ g kg}^{-1}$, respectively. The slope gradient varied from 0.06 to 0.58. The vegetation at the site primarily consists of *Artemisia ordosica* (Feng *et al.* 2014). Biocrusts have extensively developed covering approximately 75–80% of the soil surface.

Experimental design

In this study, two sets of runoff experiments were applied. Runoff experiments under natural rainfall were conducted in semiarid environments to evaluate the effects of rainfall characteristics (e.g. amount and intensity) and biocrust type on runoff yield. In addition, runoff experiments under artificial rainfall were conducted to evaluate the influence of increasing trends in intensity of heavy rainfall on runoff generation. Detailed information about the two experiments is provided in the following sections.

Runoff experiments under natural rainfall

The natural rainfall experiments were conducted during May to September 2016. There were 11 rainfall events during the study period. The dates of the 11 rainfall events were May 2, May 6, May 22, June 6, July 3, July 11, July 18, July 24, August 6, August 15, and August 20, respectively. Runoff plots

containing two biocrust types, lichen- and moss-dominated biocrusts, were set up (Table 1). Biocrusts were mainly constituted by cyanobacterial *Microcoleus vaginatus*, lichen *Collema tenax*, and moss *Bryum argenteum* Hedw., *Didymodon vinealis* (Bridel) Zander. The lichen-dominated plots primarily consisted of *C. tenax* species of lichens though there was also significant cyanobacterial cover. The moss-dominated plots, besides high moss cover, contained a certain amount of *C. tenax*. In addition, a runoff plot of the bare land was established as a control. Three plots were established for each treatment, thus totaling nine runoff plots. Runoff yield (mm) in these plots was determined after each rainfall event. The plots were constructed with 0.8-mm-thick, 20-cm-high steel sheets, which were inserted half their height into the soil. The plot size was 2.6 m^2 . All plots had a steel gutter leading to a 50-L plastic cask that was used for runoff collection (Figure 2(a)–2(c)). Rainfall was determined by a tipping-bucket gauge, with a 5-min temporal resolution and a 0.20-mm resolution, located in a site next to the plots. Maximum 5-min rainfall intensity ($I_{5\text{max}}$) and total rainfall amount were calculated for each rainfall event. An unsupervised K-means cluster was used to separate low- and high-intensity rainfall events, by explicitly searching for an ‘objective’ two-group classification based on the $I_{5\text{max}}$ and rainfall amount (Chamizo *et al.* 2012b).

Table 1 | Characteristics of different treatments under natural rainfall (Mean \pm SE)

Treatment	Bare land	Lichen-dominated biocrusts	Moss-dominated biocrusts
Area (m ²)	2.60 ^{a†}	2.60 ^a	2.60 ^a
Slope gradient (-)	0.32 ^a	0.31 ^a	0.33 ^a
Biocrust cover (%)	0.0 ^b	78.3 \pm 0.9 ^a	81.3 \pm 2.2 ^a
Algae cover (%)	0.0 ^b	24.3 \pm 4.3 ^a	0.0 ^b
Lichen cover (%)	0.0 ^c	54.0 \pm 3.5 ^a	17.7 \pm 2.3 ^b
Moss cover (%)	0.0 ^b	0.0 ^b	63.7 \pm 4.5 ^a
Properties	-	Dominated by <i>Collema tenax</i> . Dark in color	Dominated by <i>Byumargenteum</i> . Deep-green in color during the wet period and brown in color during the dry period
WDPT (s)	1.1 \pm 0.1 ^c	12.2 \pm 2.4 ^b	20.6 \pm 5.6 ^a
K_s (cm min ⁻¹)	0.17 \pm 0.03 ^a	0.11 \pm 0.03 ^a	0.03 \pm 0.01 ^b
θ_s (g g ⁻¹)	0.27 \pm 0.04 ^a	0.29 \pm 0.04 ^a	0.27 \pm 0.02 ^a
θ_f (g g ⁻¹)	0.23 \pm 0.02 ^a	0.25 \pm 0.01 ^a	0.27 \pm 0.02 ^a

WDPT, Water drop penetration time; K_s , Saturated hydraulic conductivity; θ_s , Saturated soil moisture; θ_f , Field capacity.

[†]Different letters in the same row (a,b,c) indicate significant differences at the probability level of 0.05.

Soil water repellency for each treatment was measured in the field (Figure 3) by the water drop penetration time (WDPT) method (Letey *et al.* 2000; Dekker *et al.* 2001). The measurement was conducted on August 5, 2016, before which there were no rainfall events during the previous 6 days. More specifically, three 50 μ L drops of distilled water were placed on the surface of the biocrusts, and the time elapsed to drop absorption was measured. The average time for the triple drops was defined as the WDPT. Six replications were determined at each treatment. According to this method, a penetration time of higher than 60 s implies strongly water repellent, 5–60 s implies slightly water repellent, while a time of less than 5 s indicates a lack of repellency (Bisdorn *et al.* 1993).

The average height of mosses and lichens was 1.25 and 0.85 cm, respectively. The soil water holding capacity in the top layer of 0–5 cm for each treatment, including the saturated soil moisture (θ_s , g g⁻¹) and field capacity (θ_f , g g⁻¹), was measured by a 100-cm³ metallic cutting ring. The soil infiltrability of the different treatments, which was expressed by the saturated hydraulic conductivity (K_s , mm min⁻¹), was measured using a disc infiltrometer with a diameter of 20 cm, under two pressure heads (h) of -3 and -6 cm at each location in the field (Logsdon & Jaynes 1993). The K_s was determined based on the steady state flow theory using Wooding's equation (Wooding 1968).

Runoff experiments under artificial rainfall

The artificial rainfall experiments were conducted from July 25 to August 17, 2016. A 21-cm-diameter sprinkler was used to conduct artificial rainfall (Figure 2(d)–2(f)). The average size and slope gradients for simulated plots were 0.11 m² and 0.25, respectively. The average antecedent volumetric water content for simulated plots was 0.12 cm³ cm⁻³. There was no substantial difference in the above characteristics among different treatments. The average biocrust cover for lichen- and moss-dominated biocrusts was 81 and 83%, respectively (Table 1).

The experiment also focused on the two types of biocrusts: lichen- (B1) and moss-dominated biocrusts (B2). In addition, a runoff plot of the bare land was established as the control (B0). In the experiment, three different rainfall intensities of 26, 49, and 98 mm h⁻¹ (referred to as low rainfall intensity I1, medium rainfall intensity I2, and high rainfall intensity I3, respectively) were used. Nine replications were arranged for each treatment. Therefore, 81 experimental plots were created. It is noted that the I2 level represented the actual maximum rainfall intensity in this area; however, the I3 level simulated the high-intensity rainfall in the future. The same rainfall amount was applied to each rainfall intensity level. Thus, the artificial rainfall lasted 15, 8, and 4 min



Figure 2 | Natural rainfall experiments for the bare land (a), lichen- (b) and moss-dominated biocrusts (c) and artificial rainfall experiments for the bare land (d), lichen- (e) and moss-dominated biocrusts (f).

for I1, I2, and I3, respectively. Runoff in each plot was determined when the artificial rainfall event started. The intervals of observation time were 10 seconds and 1 min before and after 5 min of artificial rainfall, respectively. The runoff coefficient for each plot was determined from the runoff yield by the artificial rainfall amount.

Numerical simulations

The HYDRUS-1D software package is a one-dimensional physically based model that can be used to simulate the movement of water, heat, and multiple solutes in variably saturated media (Šimůnek *et al.* 2013). The one-dimensional diffusion-wave equation, which is commonly used for



Figure 3 | Water droplet on the surface of the lichen- ((a) and (b)) and moss-dominated biocrusts ((c) and (d)) in the field.

describing overland flow, has recently been implemented into the popular HYDRUS-1D code.

In this work, surface runoff under varying rainfall intensities, biocrust types and slope was simulated using HYDRUS-1D. A summary of the 16 unique scenarios is presented in Table 2. Each scenario consisted of a different combination of: rainfall intensity, soil or biocrust type, and slope gradient. Five different rainfall intensities (26, 37.5, 49, 73.5, and 98 mm h⁻¹) were used in these simulations. Three soil or biocrust types (bare land, lichen- and moss-dominated biocrusts) were selected. Biocrust-covered treatment was considered as two-layer soil. The K_s of the three soils or biocrusts was considered among soil hydraulic properties. Specifically, the K_s of the bare land, lichen- and moss-dominated biocrusts was 0.17, 0.11, 0.03 cm min⁻¹, respectively. Additionally, three slope gradients (0.12, 0.27 and 0.58) were designed. The model was calibrated and validated by the runoff experiments. The initial condition for the simulations was soil water content in the upper boundary before the simulation. The upper boundary condition was defined

Table 2 | Runoff coefficient for different scenarios under numerical simulations

Scenarios #	Rainfall intensity (mm h ⁻¹)	The K_s (cm min ⁻¹) of soil or biocrusts	Slope gradient (-)	Runoff coefficient (%)
1	98	0.17	0.27	0.0
2	98	0.11	0.27	8.9
3	98	0.03	0.27	28.3
4	26	0.11	0.27	0.0
5	37.5	0.11	0.27	0.0
6	49	0.11	0.27	0.0
7	73.5	0.11	0.27	8.0
8	98	0.11	0.27	8.9
9	26	0.03	0.27	0.0
10	37.5	0.03	0.27	0.0
11	49	0.03	0.27	2.7
12	73.5	0.03	0.27	15.6
13	98	0.03	0.27	28.3
14	73.5	0.03	0.12	15.4
15	73.5	0.03	0.27	15.6
16	73.5	0.03	0.58	16.5

as atmospheric boundary condition with surface runoff. The lower boundary was simulated as free drainage.

The mean absolute error (MAE) and root mean square error (RMSE) provide a quantitative comparison of the goodness-of-fit between observed and simulated surface runoff (Moriassi *et al.* 2007). These indices were selected as the criteria for quantifying the deviation of the modeled results from the observed data:

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |O_i - P_i|$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (O_i - P_i)^2}$$

where O_i and P_i are the observed and simulated values of the i th observation. n is the number of data.

Data analysis

We used regression analysis to test the relationship between runoff yield and their best explanatory variables (rainfall amount, $I_{5\text{max}}$, WDPT, and K_s) under natural rainfall. A two-way analysis of variance (ANOVA) with nine replications was used to test whether the biocrust type, rainfall intensity, and their interaction had a significant effect on runoff generation under artificial rainfall at the probability levels of 0.05 and 0.01. The statistical analyses were conducted using SPSS 16.0 software (SPSS, Chicago, IL, USA).

RESULTS

Effects of biocrust type and rainfall characteristics on runoff under natural rainfall

As shown in Table 1, the difference in θ_f or θ_s among the three treatments was insignificant. Nevertheless, the K_s of moss-dominated treatment was significantly lower than for lichen-dominated treatment and the bare land. Moreover, the K_s for lichen-dominated treatment was slightly lower than that for the bare land, although the difference was insignificant. Both the lichen- and moss-dominated biocrusts

exhibited slight water repellency (Figure 3), and the WDPT of the moss-dominated biocrusts (WDPT = 20.6 s) was significantly higher than that of lichen-dominated biocrusts (WDPT = 12.2 s).

During the study period, there were 11 rainfall events under natural rainfall, which produced a total rainfall amount of 152.7 mm (Figure 4(a)), about 51% of the annual rainfall. The daily rainfall amount showed medium variability ($C_v = 0.75$). The mean 30-min rainfall intensity ranged between 1.1 and 5.5 mm h⁻¹ (data not shown). However, the $I_{5\text{max}}$ ranged between 6.4 and 49.5 mm h⁻¹ (Figure 4(a)). The highest rainfall amount and $I_{5\text{max}}$ were recorded in the eleventh rainfall event on August 20. The results of the K-means clustering showed that half events (55%) were low intensity, with a mean $I_{5\text{max}}$ of 11.6 mm h⁻¹, and maximum and minimum of 16.5 and 6.4 mm h⁻¹, respectively. About 45% of the events during the study period were high intensity. The highest and lowest $I_{5\text{max}}$ in the events were 49.5 and 17.8 mm h⁻¹ (mean 28.4 mm h⁻¹), with rainfall amounts ranging between 5.6 and 40.9 mm.

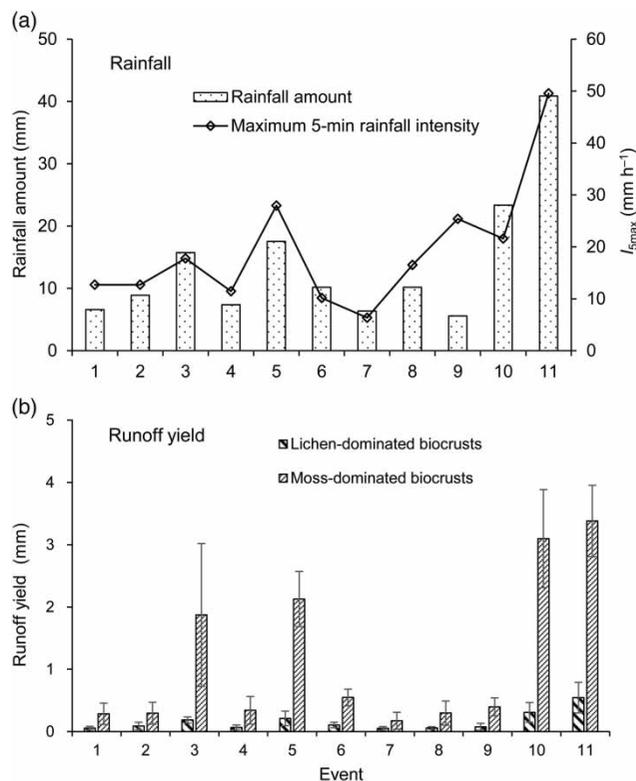


Figure 4 | Rainfall (a) and runoff yield (b) during 11 recorded runoff events under natural rainfall.

As can be seen in Figure 4(b), there was no runoff generation for the bare land treatment. The average runoff yield for moss-dominated biocrusts (1.17 ± 0.37 mm) was significantly higher than that for lichen-dominated biocrusts (0.16 ± 0.05 mm). In general, substantially higher runoff yield was observed for high rainfall amounts compared to low rainfall amounts.

Given that the relationship between rainfall amount and $I_{5\max}$ was significant (Pearson correlation coefficient = 0.862, $P < 0.001$), the two variables were regressed separately (Table 3). The results of linear regression analysis showed that when the linear regression analysis was applied to all the events and rainfall amount was considered, runoff yield was explained by rainfall amount ($P < 0.001$) and WDPT ($P = 0.001$) (regression Equation (1), Table 3). Moreover, the influence of rainfall amount on runoff yield (with standardized coefficients = 0.61) was larger than that of the WDPT (with standardized coefficients = 0.36) (regression Equation (1), Table 3). However, when the linear regression analysis was applied to the low-intensity or high-intensity events, runoff yield was explained by rainfall amount, WDPT and K_s . The relative magnitudes of the influence of rainfall amount and WDPT on runoff yield depended on the rainfall intensity. The influence of rainfall amount on runoff yield was lower than that of the WDPT for low-intensity events, while the opposite was observed for high-intensity events. In addition, the K_s could not explain runoff yield when the linear regression analysis was applied to all the events; however, runoff yield could be explained by the K_s when the linear regression analysis was applied to the low-intensity or high-intensity events. Similar results were

observed when the linear regression analysis was applied to all the events and $I_{5\max}$ was regressed (regression Equation (2), Table 3). Additionally, increasing $I_{5\max}$ significantly increased the runoff yield when the linear regression analysis was applied to the high-intensity events. Nevertheless, the opposite result was observed when the linear regression analysis was applied to the low-intensity events. WDPT can explain runoff yield regardless of the intensity of selected rainfall events when $I_{5\max}$ was considered. Whether the influence of K_s on runoff yield was significant depended on the intensity of selected rainfall events. Specifically, the K_s can explain runoff yield when the linear regression analysis was applied to low-intensity events.

Effects of biocrust type and rainfall intensity on runoff under artificial rainfall

As can be seen in Figure 5, not all treatments produced runoff, which depended on the rainfall intensity or biocrust type. For the I1 treatments, no runoff was observed except for moss-covered treatment (i.e. B2I1 treatment). For the I2 and I3 treatments, a rapid increase of runoff coefficient was observed during the first 4 min, but the runoff coefficient increased slightly after 4 min.

For the bare land treatments, there was no runoff regardless of rainfall intensity applied. The runoff coefficient between different rainfall intensity was comparable for lichen-dominated biocrusts; however, for moss-dominated biocrusts, the runoff coefficient for the I2 or I3 treatment was significantly greater than that for the I1 treatment.

Table 3 | Multiple regression analysis between runoff yield and the independent variables of rainfall amount or $I_{5\max}$, WDPT, and K_s under natural rainfall

Regression equation	Source of variation	All the rainfall events			Rainfall events with high intensity			Rainfall events with low intensity		
		Standardized coefficients	t	P	Standardized coefficients	t	P	Standardized coefficients	t	P
1	Rainfall amount (mm)	0.61	8.23	<0.001	0.48	5.21	<0.001	0.24	2.23	0.033
	WDPT (s)	0.36	3.49	0.001	0.47	3.70	0.001	0.51	3.53	0.001
	K_s (cm min ⁻¹)	-0.19	-1.89	0.064	-0.33	-2.60	0.015	-0.33	-2.32	0.027
2	$I_{5\max}$ (mm h ⁻¹)	0.54	6.48	<0.001	0.34	3.12	0.004	0.04	0.35	0.731
	WDPT (s)	0.40	3.50	0.001	0.54	3.48	0.002	0.51	3.30	0.002
	K_s (cm min ⁻¹)	-0.15	-1.33	0.188	-0.27	-1.76	0.090	-0.33	-2.11	0.043

It is noticed that the data of the bare land were not included.

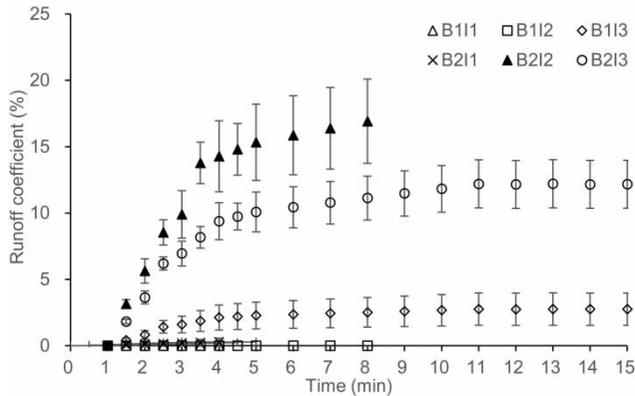


Figure 5 | Runoff coefficient for each treatment under artificial rainfall. B1 and B2 represent lichen- and moss-dominated biocrusts, respectively. I1, I2, and I3 represent low, medium, and high rainfall intensity, respectively.

As can be seen in Table 4, we found a significant difference in runoff coefficient for the I2 and I3 treatments, but no obvious difference for the I1 treatment was obtained between the two biocrust types (Figure 5 and Table 4). No runoff in lichen-dominated biocrusts was observed for the I1 and I2 treatments. In addition, the runoff yield or coefficient averaged over all three treatments for moss-dominated biocrusts was significantly greater than that for lichen-dominated biocrusts (data not shown). The

Table 4 | Runoff yield and runoff coefficient for different treatments under artificial rainfall

Treatment	Runoff yield (mm)	Runoff coefficient (%)
B0I1	0.0 ^{b†}	0.0 ^b
B0I2	0.0 ^b	0.0 ^b
B0I3	0.0 ^b	0.0 ^b
B1I1	0.0 ^b	0.0 ^b
B1I2	0.0 ^b	0.0 ^b
B1I3	0.8 ^b	2.8 ^b
B2I1	0.1 ^b	0.4 ^b
B2I2	5.2 ^a	18.5 ^a
B2I3	3.6 ^a	12.8 ^a
ANOVA		
Biocrust type (B)	$P < 0.001$	$P < 0.001$
Rainfall intensity (I)	$P < 0.001$	$P < 0.001$
B × I	$P = 0.005$	$P = 0.005$

B0, B1, and B2 represent bare land, lichen- and moss-dominated biocrusts, respectively. I1, I2, and I3 represent low, medium, and high rainfall intensity, respectively.

[†]Different letters in the same column (a,b) indicate significant differences at the probability level of 0.05.

two-way ANOVA results shown in Table 4 show that the influence of biocrust type and rainfall intensity on runoff yield or coefficient was significant at the probability level of 0.01. Furthermore, the interaction between biocrust type and rainfall intensity also imposed a significant effect on the runoff yield or coefficient at the probability level of 0.01.

Effects of rainfall intensity and biocrust type on runoff under numerical simulations

As shown in Table 2, there was no runoff for the low rainfall intensity level (26 mm h^{-1}). In addition, a higher surface runoff was observed with increasing rainfall intensity, especially when rainfall intensity increased from 49 to 73.5 mm h^{-1} . For example, for moss-dominated biocrusts, runoff coefficient for rainfall intensity of 73.5 mm h^{-1} (scenario 12) was 5.8 times higher than that for 49 mm h^{-1} (scenario 11). There was no runoff for the bare land treatment, although the rainfall intensity reached 98 mm h^{-1} . Conversely, surface runoff was generated for lichen- and moss-dominated biocrusts when rainfall intensity reached 73.5 and 49 mm h^{-1} , respectively. The runoff coefficient averaged different rainfall intensities for the moss-dominated soil and was 175.7% higher than that for the lichen-dominated soil. A higher slope slightly increased the runoff coefficient in the moss-covered soil under the rainfall intensity of 73.5 mm h^{-1} .

DISCUSSION

Relationship between biocrusts and runoff

The occurrence of biocrusts usually influences soil water redistribution in semiarid areas (Cantón *et al.* 2011; Maestre *et al.* 2011; Xiao *et al.* 2011; Yang *et al.* 2015). After monitoring runoff under natural rainfall in moss- and lichen-covered plots for one year, we found that runoff generation was observed in moss- and lichen-covered soils except for the low rainfall intensity, although the runoff yield was low (Figure 4(b)). Similar results were also concluded by numerical simulations (Table 2). Previous studies also reported that larger runoff yield was observed in biocrust-covered soils

compared to bare soils. Wu *et al.* (2012) also reported that runoff was observed on biocrust-covered soils during some rainfall events in the Mu Us Desert. This phenomenon was attributed to the repellent properties of mosses and lichens compared to bare land (Table 1). Furthermore, higher fine content (i.e. silt and clay) was observed for biocrust-covered soil compared to bare soil. In addition to greater water repellency of biocrust-covered soils, lower K_s compared to bare soils is associated with decreased water infiltration and increased runoff (Table 1).

Infiltration is influenced by the water residence time and the permeability of the soil surface (Eldridge & Greene 1994). Generally, lichen- and moss-dominated biocrusts could increase infiltration by enhancing soil surface roughness and water retention capacity (Rodríguez-Caballero *et al.* 2012). Biocrusts are smooth in hyperarid hot deserts, whereas biocrusts have irregular surfaces in cold deserts. Therefore, water retention time is longer and water infiltration is higher in cold deserts than in hyperarid hot deserts (Belnap 2006). In our study, biocrusts have a moderate roughness between those of cold and hyperarid deserts. Moreover, mosses (about 1.25 cm height) have slightly higher surfaces than lichens (about 0.85 cm height), and therefore are similarly effective at influencing runoff with the lichens. However, higher amounts of silt and clay in mosses likely led to lower K_s than in lichens, which could explain the significantly higher runoff yield for the moss-covered treatments compared to the lichen-covered treatments (Kidron 2015; Rodríguez-Caballero *et al.* 2015a). These results suggest that biocrusts influenced surface runoff by changing soil properties. Similar results were also reported by other researchers (e.g. Fischer *et al.* 2010; Li *et al.* 2010).

After monitoring runoff under artificial rainfall in lichen- and moss-covered plots, we found that the difference in runoff coefficient between lichen- and moss-dominated biocrusts depended on rainfall intensity (Table 4). Similar to our findings, Cantón *et al.* (2004) indicated that the effects of lichens on water infiltration could depend on rainfall intensity. Lichens appeared to enhance water infiltration and increase soil moisture at low rainfall intensity, whereas they could increase runoff at high rainfall intensity (Cantón *et al.* 2004). When rainfall intensity is low, soil surface roughness and surface storage capacity caused by biocrusts inhibited runoff generation. When rainfall intensity is high, water in soil

depressions keeps for a short time before overland flow occurs. Therefore, the influence of soil surface roughness and surface storage capacity enhanced by biocrusts on runoff could be alleviated by the effects of rainfall intensity (Chamizo *et al.* 2012b). Furthermore, lichen biocrusts are prone to being broken and cause soil depressions by raindrops under high rainfall intensity, which resulted in increasing infiltration and decreasing runoff yield. However, a similar phenomenon was not observed in moss-dominated biocrusts. This resulted in significantly larger runoff coefficient for moss-dominated biocrusts than that for lichen-dominated biocrusts under the medium- and high-intensity rainfall events.

Relationship between rainfall characteristics and runoff

Natural rainfall experiments showed that substantially higher runoff yield was observed for high rainfall amounts compared to low rainfall amounts. However, in this study, the low rainfall amount event yielded a higher runoff yield than the high rainfall amount event (e.g. events 8 and 9 in Figure 4(b)). This could be explained by higher rainfall intensity in the ninth rainfall event in comparison to the eighth event. This result suggests that runoff yield is not only dependent on rainfall amount, but is also influenced by rainfall intensity. In this study area, rainfall events during the study period included two types of rainfall events: short, high-intensity rainfall and long, low-intensity rainfall. Similarly, Cantón *et al.* (2002) reported the two rainfall types in a semiarid ecosystem. After measuring runoff under natural rainfall, we found that the difference in runoff yield between lichen and moss biocrusts increased with increased rainfall amount (Figure 4). Wu *et al.* (2012) also reported that similar runoff yield was observed among three types of biocrusts when the rainfall amount was low (~12 mm); however, runoff yield was greater for well-developed biocrusts (e.g. mosses) than for the low-developed biocrusts (e.g. light algae) under high rainfall amounts (~22 mm). In addition, we concluded that the rainfall amount or $I_{5\max}$ was the main factor explaining runoff variation under natural rainfall (Table 3). In agreement with our results, Mayor *et al.* (2011) also indicated that rainfall amount could better predict runoff yield for most rainfall events in semiarid regions, although rainfall intensity still could be a good predictor of runoff for high-intensity rainfall events.

After monitoring runoff yield under artificial rainfall, we concluded that there was no runoff for low rainfall intensity treatment; however, runoff generation was observed for medium or high rainfall intensity treatments. Similar results were also observed under numerical simulations (Table 2). Belnap *et al.* 2013 also reported that runoff is usually nonexistent for pinnacled biocrusts, except for extreme rainfall events in semiarid regions. In addition, we found that rainfall intensity exerted a strong influence on runoff, and had a significant effect on the relationship between biocrust type and runoff (Table 4). This suggests that runoff could be changed substantially under increasing trends in intensity of heavy rainfall, and the response of runoff to biocrust type depended on rainfall intensity in the Mu Us Desert. Similarly, Yu *et al.* (2010) reported the simulated results regarding the effects of biocrusts on soil hydrological processes in the Tengger Desert. They concluded that no runoff was observed during low-intensity rainfall events; however, during higher-intensity rainfall events, the lower saturated hydraulic conductivity for biocrust-covered treatment resulted in greater runoff than that for the bare land treatment. Additionally, although significantly higher runoff yield or coefficient was observed by the I2 or I3 treatment in comparison to the I1 treatment, the value for the I3 treatment from moss-dominated biocrusts was lower than that for the I2 treatment. For the moss-dominated biocrusts, the different response of runoff yield or coefficient to the increased rainfall intensity may be attributed to a lower slope gradient for the I3 treatment compared to the I2 treatment, which could alleviate the positive influence of rainfall intensity on runoff generation (data not shown). In addition, on the contrary, the results of numerical simulations showed that runoff yield in the moss-dominated soil substantially increased with increasing rainfall intensity. The results of numerical simulations showed that the MAE and RMSE values were 4.4 and 7.8%, respectively (data not shown). This result indicates that there was no good fit between observed and simulated surface runoff. Uncertainty in surface runoff estimates is inevitable. Uncertainty in the soil hydraulic properties in the numerical simulations contributes to uncertainty in estimating the surface runoff. In addition, preferential flow could also exist in the field and enhance uncertainty in surface runoff. The reasons mentioned above resulted in the high MAE and RMSE values between observed and simulated surface runoff.

However, we should realize that the mechanism about the influence of biocrusts on runoff generation is not fully understood. First, the rainfall intensity was steady during the artificial rainfall experiments and numerical simulations. However, the specific rainfall intensity and duration in natural rainfall was unsteady or changed dramatically in the semiarid area (Dunkerley 2018). Nevertheless, few studies about the effects of varied rainfall intensities on the relationship between biocrust type and runoff was reported in semiarid areas. Secondly, tunnels caused by roots or ants are usually found in moss-dominated biocrusts (Kidron 2016), which could result in preferential flow. This preferential flow could alleviate the influence of biocrusts on runoff. Therefore, further studies will be needed to evaluate the influence of varied rainfall intensity and preferential flow on runoff generation. In addition, biocrusts may influence soil moisture by changing soil hydrological processes (e.g. evaporation, infiltration, and runoff), and thus affect the growth of shrub vegetation (Xiao & Hu 2017). However, the effect of biocrusts on soil water content and shrub vegetation have not been sufficiently evaluated. Accordingly, studies on the influence of biocrust type on soil moisture and the growth of artificially planted shrub will also be needed.

CONCLUSIONS

Runoff experiments under natural and artificial rainfalls and numerical simulations were conducted in semiarid environments to evaluate the effects of biocrust type and rainfall characteristics (e.g. amount and intensity) on runoff. The results showed that the moss- and lichen-dominated biocrusts exhibited slight water repellency. Moreover, a significantly higher WDPT was observed for the moss-dominated biocrusts compared to the lichen-dominated biocrusts. However, the K_s for moss-dominated biocrusts was significantly lower than lichen-dominated biocrusts. Runoff yield for moss-dominated biocrusts was significantly higher than lichen-dominated biocrusts. Rainfall amount (or $I_{5\max}$) and WDPT were identified as the crucial factors determining runoff yield. The influences of biocrust type, rainfall intensity, and their interaction on runoff coefficient were significant at the probability level of 0.01. The results of numerical simulations concluded that surface runoff was

generated for lichen- and moss-dominated biocrusts when rainfall intensity reached 73.5 and 49 mm h⁻¹, respectively. Runoff coefficient in the moss-covered soil increased obviously when rainfall intensity changed from 49 to 73.5 mm h⁻¹. Additionally, a higher slope slightly increased runoff coefficient in the moss-covered soil. The results suggest that lichen- and moss-dominated biocrusts play different roles in runoff generation, and runoff could be changed substantially under increasing trends in rainfall intensity in the Mu Us Desert.

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