

Characteristics of surface runoff in a sandy area in southern Mu Us sandy land

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To better understand the key role of biological soil crusts (BSCs) in redistribution processes of limited water resources in semi-arid sandy ecosystems, surface runoff over BSCs in a sandy area in the southern Mu Us sandy area was observed in this study. The results indicated that runoff occurred twice among six rainfall events during the experimental period. Runoff yields varied among types of BSCs, and that they increased in the following order: light algae crusts, dark algae crusts and moss crusts. These findings showed that runoff yields were increasing with the development of BSCs. The percentage of runoff in individual rainfall events increased from light algae crusts to moss crusts, which indicated that the redistribution ratios of different types of BSCs differed. Surface runoff of BSCs may be influenced by rainfall, rain intensity, degree of water saturation of the BSCs before the rain and degree of development of BSCs. Formation of BSCs on the surface of sand dunes changed the spatial distribution pattern of water in this semi-arid sandy ecosystem, which increased the heterogeneity of resources such as water and nutrients. Therefore, making appropriate disturbances of BSCs during storm season is beneficial to maintaining the balance of natural resources in the semi-arid sandy ecosystem.

Mu Us sandy land, sand dune, biological soil crusts, runoff

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There is a widespread perception that surface runoff is unlikely to occur in sandy areas owing to the high infiltration rate of sand (up to 300 mm h^{-1}) [1]. However, the presence of thin biological soil crusts (associated compositions of bacteria, microfungi, cyanobacteria, lichens, and bryophytes with soil particles, BSCs) on the surface of sand dunes has significant effects on water infiltration; therefore, their presence makes the generation of runoff possible. The formation and development of BSCs on the surface of sand dunes has profound effects on local hydrological cycles [2]. Thus, determination of how the presence of BSCs affects infiltration or runoff has been the focus of many hydrological studies. However, there is little agreement regarding how BSCs affect water infiltration and runoff. A considera-

ble amount of literature has reported that the presence of BSCs decreases infiltration and increases runoff [3–10], or increases infiltration and decreases runoff [11–13], while some studies have shown that they have no effect on either process [14,15]. Studies of the Shapotou artificial vegetation restoration system in the Tengger desert have indicated that the formation and development of BSCs can lead to interception of water and keep it away from the deep soil layer [16–20]. Simulated rainfall experiments of the effects of BSCs on water infiltration have shown that runoff only occurred when the diurnal rainfall intensity exceeded 40 mm. However, this type of rainfall event was rare in arid areas, where annual rainfall is often less than 200 mm [17–19]. Indeed, no runoff was collected during natural rainfall events because the rainfall completely infiltrated the sandy land. Thus, the present understanding of the influence

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of BSCs on local water infiltration or runoff is limited owing to the complex intercepting process over BSCs. Indeed, different researchers hold different or even controversial views regarding the influence of BSCs on water infiltration and runoff. Thus, far more data must be collected before any generalizations regarding how BSCs influence water infiltration and runoff can be made.

In China, deserts are widely distributed in arid and semi-arid regions. After several decades of sandification control and ecological rehabilitation, BSCs have become well developed on the surface of fixed and semi-fixed sand dunes. To date, most studies of the influence of BSCs on water infiltration or runoff have been conducted in arid sandy areas. However, less attention has been paid to the role that BSCs play in water infiltration or runoff in semi-arid sandy ecosystems, where the annual average rainfall reaches approximately 400 mm. In this study, the characteristics of surface runoff in semi-arid sandy areas were investigated, the percentage of runoff in individual rainfall events was determined, factors influencing runoff generation were discussed, and the causes of long-term international debate regarding how BSCs in different regions influence water infiltration or runoff were explained. The results presented herein have deepened our understanding of the role of BSCs on water redistribution processes in semi-arid sandy regions, and provide information that will be useful in determining the rational use and rehabilitation of damaged ecosystems.

1 Materials and methods

1.1 Site description

The experiment was conducted at Jingbian Desert Experimental Research Station of Beijing Normal University (Figure 1), which is located in the southern fringe of the Mu

Us sandy land, a transitional zone between the Ordos Plateau and Loess Plateau (Jingbian County, Yulin, Shaanxi Province, 37°38'N, 108°50'E, 1350 m a.s.l.). The mean annual precipitation in the study area is 395 mm, with a maximum value of 745 mm (in 1964) and a minimum of 205 mm (in 1965), most of which occurs in summer and autumn. The mean annual temperature is 7.9°C, the average annual evaporation is 2485 mm, and the mean annual arid index is 2.3.

The study area is located in a steppe in a warm temperate zone in northern China in a transitional area between a typical steppe and forest steppe. Local landforms consist of fixed dunes and semi-fixed dunes with psammophyte species that primarily consist of *Artemisia ordosica* Krasch, *Agriophyllum squarrosum* (Linn.) Moq., *Corispermum puberulum* Iljin, and *Psammochloa villosa* (Trin.) Bor. The soil types included sandy soil, fixed sandy soil and meadow soil.

1.2 Methods

Runoff samples from different types of BSCs in artificially revegetated areas of the research station were collected. The characteristics of BSCs are shown in Table 1. Runoff plots were installed on the surface of light algae crusts (LC), dark algae crusts (DC) and moss crusts (MC). Runoff plots were constructed of PVC pipes (40 cm in diameter and 15 cm in height). A mouth of 2.5 cm in diameter was opened in the PVC pipes using an electric drill and smaller pipes (2.5 cm in diameter and 5 cm in height) were connected to the mouth to form an outlet (Figure 2). The joints were sealed with glue to prevent leaking. The bottom fringe of the PVC pipe was sharpened using an electric drill to minimize the impact of the pipe thickness on the crust layer and subsurface soil. The surfaces of the BSCs were wetted before installation of the runoff plots using a watering can to avoid

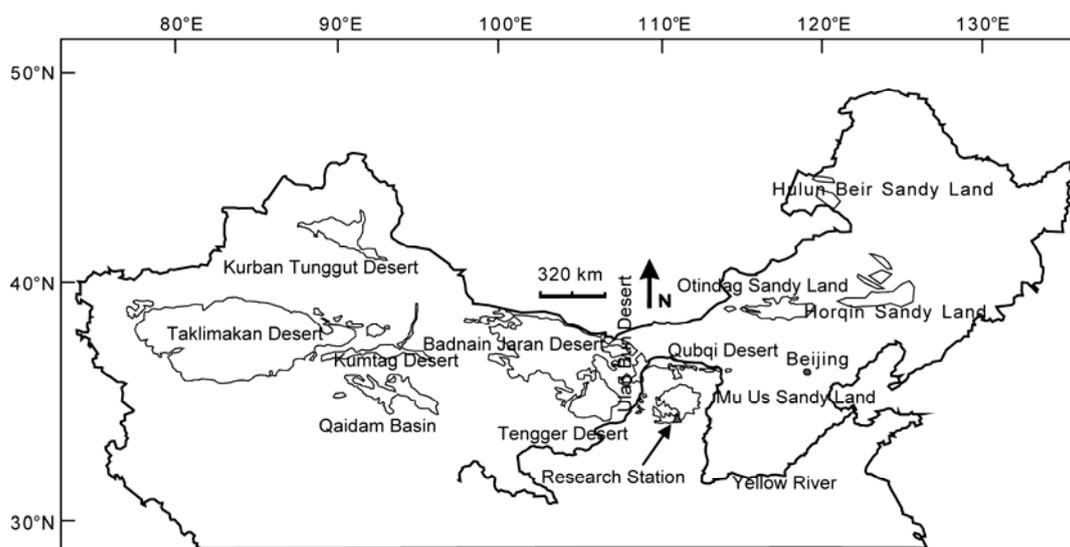


Figure 1 Location of the research station.

Table 1 Characteristics of biological soil crusts in the study area

Type	Number	Slope angle (°)	Properties
Light algae crusts	LC	26	Dominated by <i>Oscillatoria</i> spp., <i>Lyngbya</i> spp. Light in color, with a smooth surface, 3–5 mm thick and a gear strength of 0.3–0.5 kg cm ⁻²
Dark algae crusts	DC	27	Dominated by <i>Oscillatoria</i> spp., <i>Lyngbya</i> spp. Light in color, with a course surface, 5–8 mm thick and a gear strength of about 1 kg cm ⁻² . Mainly composed of silt and clay with particles finer than sand and light algae crusts
Moss crusts	MC	27	Dominated by <i>Bryum dichotomum</i> Hedw. and <i>Bryum argenteum</i> Hedw. 10–12 mm, with a gear strength of 2.1 kg cm ⁻² . Deep-green color during rainy season and brown in dry season. More flexible and less prone to being broken when compared to physical crust and algal crust

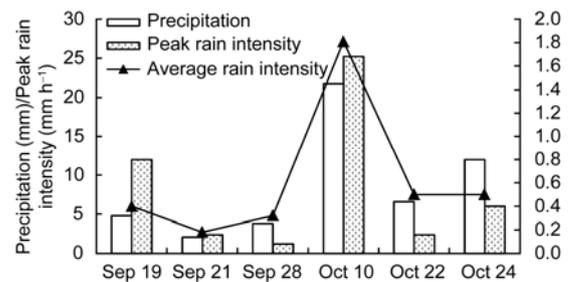
**Figure 2** Runoff plots.

disturbance. The PVC pipes were placed into sand surfaces vertically that were covered with representative BSCs and checked to ensure the water generated in the runoff plots flowed out smoothly. The outlet was connected to a collecting bottle used to store the runoff via plastic tubes. A recording rain gauge was used to determine the amounts of runoff collected in the bottle after rainfall. There were three replicate runoff plots installed in each crust type. Owing to the very limited crust heterogeneity, the systems were installed compactly to minimize the effects of heterogeneity of the BSCs on the runoff yields. A standard rain gauge and a tipping bucket rain gauge (RG1, Delta-T, Cambridge, UK) were used to measure the amount and intensity of the rainfall. The differences in runoff yields on different crust types and the percent runoff in individual rain events were compared by ANOVA followed by Tukey's honestly significant difference test ($p < 0.05$).

2 Results and analysis

2.1 Rainfall characteristics

During the experimental periods, there were six rainfall events that produced a total of 51.1 mm of precipitation (Figure 3). The precipitation in the individual events was 4.8, 2.1, 3.8, 21.8, 6.6 and 12 mm, covering 8.2%, 4.1%, 7.4%, 42.6%, 12.9% and 23.5% of the total rainfall, respectively. The average rainfall intensity of each event was 0.4,

**Figure 3** Characteristics of rainfall in the study area during the experimental periods.

0.18, 0.32, 1.81, 0.5 and 0.5 mm h⁻¹ and the peak rain intensity was 12, 2.4, 1.2, 25.2, 2.4 and 6 mm h⁻¹, respectively. Three rainfall events had peak rain intensities exceeding 6 mm h⁻¹, covering 50% of all rainfall events. The highest precipitation, peak rain intensity and average rain intensity were recorded on October 10. Overall, although rainfall in the study area during the experimental periods was characterized by several large rainfall events, a few large storms accounted for the majority of rainfall.

2.2 Characteristics of runoff

Surface runoff was collected in October 10 ($P=21.8$ mm) and October 24 ($P=12$ mm) (Figure 4). Runoff yields varied among BSCs. When the individual rainfall was 21.8 mm, the runoff yields in areas with different types of BSCs were as follows: LC (1.9±0.5) mm, DC (3.4±0.6) mm and MC (3.5±0.5) mm. The runoff yields in the DC and MC plots were significantly higher than that in LC plot ($p < 0.05$), but no significant difference was observed between runoff yields in the DC plot and the MC plot ($p > 0.05$). When the individual rainfall was 12 mm, the runoff yields from different types of BSCs were as follows: LC (1.1±0.3) mm, DC (1.1±0.5) mm and MC (1.7±0.6) mm. There were no significant differences in runoff yields among BSCs ($p > 0.05$). The percentages of runoff from individual rainfall events were varied and consistent with the changes in runoff yields among BSCs. The percentages of runoff during the two rainfall events among crusts were as follows: LC (8.8±2.4%); DC (15.8±2.9%); MC (15.9±2.2%); LC (9.2±2.7%); DC (9.3±4.3%) and MC (14.0±5.2%). These findings indicated that there were some differences in the redistribution ratio among different types of BSCs.

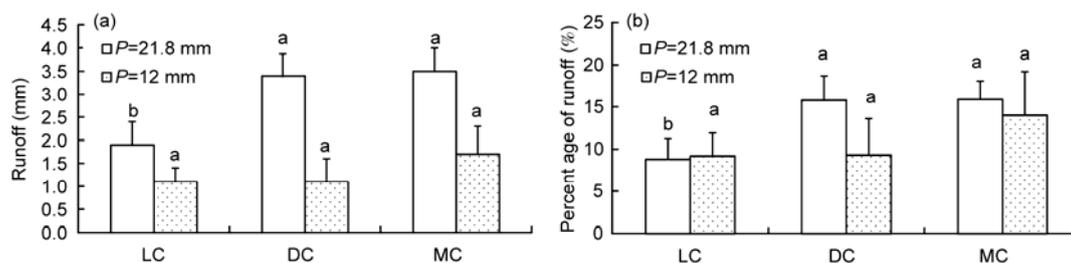


Figure 4 Runoff yields over the surface of the BSCs (a) and percentage of runoff in individual rainfall (b). Different small letters in the same column indicate significant differences at the 0.05 level.

3 Discussions

3.1 Effects of rainfall on runoff

Runoff occurred twice in six rainfall events during the experimental period and runoff was not generated during each rainfall event. When compared with rainfall that generated no runoff, rainfall events that produced runoff were characterized by greater amounts of precipitation. These findings demonstrated that the amount of rain is a crucial factor determining whether runoff from BSCs is produced or not. In addition, the average rainfall intensity and peak rainfall intensity of the two rainfall events in which runoff occurred were higher than in rainfall events in which no runoff was generated. Although the peak rainfall intensity on September 19 (12 mm h^{-1}) was higher than that on October 24 (6 mm h^{-1}), no runoff was generated in the former rainfall event. Conversely, runoff was collected during the latter rainfall event, indicating that the instantaneous rainfall intensity is not the crucial factor determining whether runoff would occur or not over the surface of the BSCs. Studies of the Negev desert have indicated that rainfall intensity in excess of 12 mm h^{-1} at the beginning of a rainstorm is not sufficient for the generation of runoff. Rather, runoff occurs when the soils are wet at the end of the storm [1]. These findings are in accordance with the results of the present study. Further analysis indicated that, although the average intensity of rainfall events on September 19, October 22 and October 24 were similar, runoff was only collected during the rainfall event on October 24. These findings may be explained by the rainfall event on October 22. Specifically, although no runoff was generated during the October 22 rainfall event, it wet the surface of the BSCs, which made it easier to generate runoff during the next rainfall event. Hence, the BSCs of the Mu Us sandy area are not water-repellent, but can absorb a large amount of water when the BSCs are dry, thereby preventing the generation of runoff, even when the peak rain intensity is as high as 12 mm h^{-1} . Runoff can occur in response to lower peak rain intensity (6 mm h^{-1}) when the surface of the BSCs are already wet or saturated.

3.2 Effects of BSCs on runoff

The finding that runoff yields from different types of BSCs

changed significantly indicates that the surface runoff from sand dunes is not only influenced by the characteristics of rainfall, but also by the type of BSCs. Differences in runoff yields among BSCs can be influenced by variations in the biotic and abiotic composition of BSCs.

(i) Effects of abiotic factors. The mechanical composition of different types of BSCs varied significantly (Table 2). Airborne silts and clays trapped by sticky cyanobacterial sheaths, protruding moss stems and lichen thalli and surface roughness created by BSCs increase the fine texture contents of BSCs continually. Additionally, formation of BSCs on the surface of sand dunes increases the contents of secondary minerals by weathering the original minerals, leading to decreased soil particle size, which leads to a finer texture of BSCs [21]. As a result, well-developed BSCs contain a finer texture than less-developed BSCs.

The duration and amount of runoff are, to a large extent, determined by the soil infiltration capacity, which is influenced by soil porosity and the duration of runoff on the soil surface [22]. During rainfall events, dust that has fallen on the crust seals the matrix porosity of the BSCs, reduces the hydraulic conductivity of the soil surface, prolongs the time for which water remains in the surface of BSCs, and decreases the water infiltration, thereby generating a large amount of runoff [22,23]. Electron microscopy analysis revealed that the upper 1–2 mm layer of the BSCs is typically nonporous when compared with the soil below. Thus, it is probable that hydraulic penetration and water entry would be limited during most rainfall events [24]. Finer texture contents of well developed BSCs likely have a more significant pore clogging effect in the early stage, and create more runoff over the surface of well developed BSCs.

(ii) Effects of biotic factors. Variations in biotic components in different types of BSCs may be another crucial factor that influences runoff yields. Crust organisms have dual effects on runoff generating processes. Specifically, crust organisms can absorb up to 10 times their volume and 8–12 times their dry weight in water owing to their ability to swell upon wetting. Additionally, the swelling of crust organisms (cyanobacteria or hyphae of free-living fungi) could exclude water by occupying the matrix pore in the crust layer, thereby reducing infiltration and increasing runoff [25]. Conversely, once the surface becomes wetted,

Table 2 Characteristics of mechanical composition of different types of biological soil crusts

Type	Contents (%) (Particle size: mm)						
	1–0.5	0.5–0.25	0.25–0.0625	0.0625–0.031	0.031–0.0156	0.0156–0.0039	0.0039–0.0005
Bare sand	0.00	26.92	73.08	0.00	0.00	0.00	0.00
LC	0.00	21.19	73.45	0.62	2.50	1.46	0.79
DC	0.00	17.79	72.19	3.92	3.39	1.89	0.83
MC	0.00	12.64	63.28	12.58	5.45	3.48	2.58

swelling microbial exudates such as extracellular polymeric substances (EPS) may clog the pore space, reducing hydrological conductivity [26]. According to Chenu [27], typical amounts of EPS range from 10% to 500% of the cell biomass. Large amounts of EPS produced in soil can clog soil pores and then reduce soil porosity, reduce the hydraulic conductivity of the soil surface, decrease water infiltration, and finally generate runoff [24,25,28]. In addition, most crust organisms are concentrated on the surface of the crust layer. Cyanobacteria strands are less likely to clog pores than lichens and mosses because the latter are large enough to cover soil pores completely. Mosses can absorb water directly or trap water in their specialized leaf structures and then transport it to their stems via special leaf arrangements, resulting in reduced water infiltration [2]. Thus, well developed BSCs intercept more water because of their specific structure on the surface, resulting in less penetration into deeper soil layers.

Overall, surface runoff over sand dunes can be simultaneously affected by rainfall, rain intensity, the degree of water saturation of the BSCs before rain and the type of BSCs. Although our study did not completely clarify the runoff generation processes on the surface of sand dunes, it has deepened our understanding of the role of BSCs in water redistribution processes of limited water resources in semi-arid sandy ecosystems; therefore, the results presented here have obvious significance in rational use and rehabilitation processes of damaged ecosystems.

3.3 Ecological significance of BSCs in water redistribution

In dry land ecosystems, which are characterized by vegetation interspersed in a matrix of bare crusted soils, surface runoff is a dominant pathway for resource transportation (e.g. water, nutrients or seeds) and redistribution within the landscape [22,23,29,30]. During the rainfall events observed in our experimental period, approximately 8.8%–15.9% of the rainwater was redistributed by surface runoff. In addition, 80% of the annual precipitation occurred in summer and autumn, and most of this was in the form of rain [31]. The redistribution of rainfall by BSCs increased as the rain intensity became stronger.

Formation of BSCs on the surface of sand dunes changed the local water distribution pattern, which had profound effects on the functions and processes of semi-arid sandy

ecosystem. Specifically, runoff generated on the surface of BSCs was redistributed to lower parts of the sand dune and other patchy areas, which led to an increase in the spatial heterogeneity of water. Therefore, organisms distributed in this region will receive more water, which will consequently affect plant germination, biodiversity and distribution patterns [1,29,32]. Moreover, BSCs can fix CO₂ and nitrogen in the atmosphere [33,34]. Considerable dissolved carbon or nitrogen were triggered by surface runoff from the crust patches to the lower parts of the sand dune and bare crusts patches, which increased the nutrient heterogeneity of the semi-arid sandy ecosystem, resulting in the organisms distributed in these regions receiving more water and nutrients, thereby affecting the functions and processes of the semi-arid ecosystem [22,35]. In addition, extensive development of BSCs on the slope surface provided a larger area of catchments, which may generate a large amount of runoff and increase the surface erosion of BSCs during rainstorm events. The effect of BSCs with smaller areas on the redistribution processes of precipitation are reflected as increased water and nutrient heterogeneity. Therefore, making appropriate disturbances to BSCs during storm season is beneficial to maintaining the balance of natural resources in semi-arid sandy ecosystems.

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