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Development of artificial moss-dominated biological soil crusts and their effects on runoff and soil water content in a semi-arid environment

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ABSTRACT

Artificial biological soil crusts (hereafter 'crusts') are promising candidates for the control of soil and water loss in semi-arid ecosystems. However, their hydrological functions have not yet been sufficiently investigated. In this study, runoff plots were constructed in a semi-arid environment on the Loess Plateau of China, and moss-dominated crusts were later artificially cultured. The effects of the artificial crusts on runoff and soil water content (0–90 cm) over eight years (2005–2012) were determined, depending on the differences between the artificial crusts and no crusts. The results showed that (1) artificial moss-dominated crusts primarily developed after two years and fully formed after four years in the semi-arid environment; (2) artificial crusts reduced runoff by 27% in total in the first three years after the inoculation; (3) artificial crusts decreased soil water content, and this effect increased linearly with time; and (4) artificial crusts increased water content in the upper 20 cm of soils but reduced water content in deeper (>30 cm) soils. The results indicate that it is feasible to artificially culture moss-dominated crusts in semi-arid regions. However, artificial crusts only slightly improved surface soil water conditions and greatly impaired deeper soil water conditions.

1. Introduction

Vegetation degradation and desertification due to climate change and human activities in arid and semi-arid regions represent two of the most significant global environmental problems of our time (Verstraete et al., 2009). It has been reported that vegetation covers only approximately 5% of some desertified areas (e.g., the Loess Plateau in China) as a result of long-term scarce precipitation, intensive evaporation, and major soil and water losses (Wang et al., 2008). However, biological soil crusts (crusts) cover 40–100% of the open ground surface in these regions and represent one of the most important components of vegetation and land cover (St Clair et al., 1993; Xiao et al., 2011b). The filaments and rhizoids of the living components of crusts weave through the top few millimeters of soil and bind loose soil particles together, forming a special matrix layer on the original soil surface (Belnap and Lange, 2003; Tisdall et al., 2012). It has been reported that the physical, chemical, and biological properties of surface soil, such as its roughness, texture, porosity, absorptivity, color, organic matter content, fertility, hydraulic parameters, biodiversity and activity, are greatly influenced by crusts at multiple scales (e.g., Zhao et al., 2010; Menon et al., 2011; Chamizo et al., 2012b). Crusts have ultimately been recognized as a component that exerts a major influence on arid and semi-arid ecosystems (Belnap, 2006; Maestre et al., 2011).

Due to the important functions of crusts in arid and semi-arid ecosystems, mainly including stabilizing soil surface and conserving soil and water (Belnap and Lange, 2003), it is expected that crusts could eventually be artificially cultured and propagated to control soil and water loss, which could lead to desertification (Wei, 2005). A number of studies have been conducted to test the feasibility of artificially culturing different types of crusts under laboratory or field conditions in different climate regions. For example, Chen et al. (2006) reported that the algal-dominated

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crusts formed in a short time and could resist the erosion of wind and rainfall for 22 days after inoculation in Inner Mongolia, China; Wang et al. (2009) assessed the feasibility of crust formation via cyanobacteria inoculation in desert areas in Inner Mongolia, China; Tian et al. (2005) found that the moss-dominated crusts completely covered soil surface after one month inoculation in Tengger Desert, China; Xiao et al. (2011b) confirmed that the moss-dominated crusts almost completely covered soil surface after about 10 months in the laboratory using a natural crust inoculum from the Loess Plateau, China. Although the studies affirmed that it was feasible to artificially grow algae-, cyanobacteria-, or moss-dominated crusts through inoculation, the ecological functions of these artificial crusts in arid and semi-arid ecosystems are not clear. Artificial crusts possibly have very different functions, compared to natural crusts, due to their fast growth rates under human-made favorable conditions (e.g., moisture, light, and nutrients), although they are similar in appearance (e.g., density, height, and color) and even in species composition (Dojani et al., 2011; Xiao et al., 2011b). Owing to the scarcity and importance of water in arid and semi-arid ecosystems, the hydrological functions of artificial crusts, for example in changing runoff generation and soil moisture regimes, are especially important, however, rarely investigated. Furthermore, research on the hydrological functions of natural crusts globally has led to contradictory conclusions, indicating that the influence of natural crusts on infiltration and evaporation is positive (Zhang et al., 2008; Xiao et al., 2011b), negative (Xiao et al., 2007; Kidron and Tal, 2012), or neutral (Xiao et al., 2010; Chamizo et al., 2012a).

We hypothesized that moss-dominated crusts could be artificially cultured in semi-arid environments, and that these artificial crusts could significantly influence runoff generation and soil water content. Based on these hypotheses, we constructed runoff plots in a semi-arid environment on the Loess Plateau of China, and moss-dominated crusts were then artificially cultured. The coverage of artificial crusts was then measured continuously, and the runoff and soil water content (0–90 cm) in the plots with and without artificial crusts monitored over eight years. The objectives of this study were to (1) describe the development of the artificial crusts from zero to full coverage; (2) determine the effects of the artificial crusts on runoff; and (3) assess the influences of the artificial crusts on soil water content at different soil depths. This study could be useful to understand the hydrological functions of artificial crusts and their potential for soil and water conservation, in semi-arid regions.

2. Materials and methods

2.1. Study site description

The study was carried out in the Liudaogou watershed (38°46′–38°51′ N, 110°21′–110°23′ E) located in north of the Loess Plateau, China. The average annual precipitation and potential evaporation are 409 and 1337 mm, respectively (Xiao et al., 2011a). The annual mean temperature is 8.4 °C with the highest mean temperature of 23.7 °C in summer and the lowest mean temperature of −9.7 °C in winter (Xiao et al., 2011a). Natural moss-dominated crusts are extensively developed in this watershed, with coverages reaching to 70–80% (Xiao et al., 2010). The soil at the study site was a loess soil (Los-Orthic-Entisol), and it presented a clayey texture, with 10% sand, 35% silt, and 55% clay. The field capacity, saturated water content, and saturated hydraulic conductivity were 0.37 $cm^3\ cm^{-3}$, 0.43 $cm^3\ cm^{-3}$, and 11.5 $cm\ h^{-1}$, respectively. The topsoil pH, organic matter, available nitrogen, and phosphorus contents were 8.8, 0.36%, 20.8 $mg\ kg^{-1}$, and 5.2 $mg\ kg^{-1}$, respectively.

2.2. Experimental design

Three independent variables were considered: soil cover (two levels: artificial crusts and no crusts), time (covering a total of 25 field campaigns conducted after the inoculation of crusts), and soil depth (covering 0–90 cm at 10 cm intervals). According to the experimental design, two treatments (artificial crusts and no crusts, defined as control) with three replications were set up, and corresponding six hydraulically isolated plots (5.0 m length and 3.0 m width with a V-shaped runoff collection area) with 14% slope gradient were constructed. The top 10 cm of soil in the plots was first plowed, after which the carbonate nodules were removed, and clods of soil greater than 10 mm were sieved out and broken into pieces. Finally, the soil surface was smoothed to produce an even northwest-facing slope.

2.3. Artificial propagation of crusts

The natural crusts collected from the local environments were air dried in the dark, and then crushed with a grinding machine with a 2 mm mesh screen. These collected natural crusts were dominated by *Bryum arcticum* (R. Brown) B.S.G. and *Didymodon vinealis* (Brid.) Zander. On the pretreated soil surface in the plots, the crushed natural crusts were mixed with fine soil (1:4 in mass) and distributed uniformly at a rate of 1.25 $kg\ m^{-2}$ air-dried matter on August 4, 2005. The soil surface was then immediately irrigated with a sprinkler that could generate very fine and gentle water drops. The irrigation took several minutes, as determined by the wetness of the surface soil (sufficiently wet but without surface runoff). The irrigation was repeated every 3–5 days and lasted until the end of May in 2006, when well-developed artificial crusts had initially formed. During this period, 20 g of KH_2PO_4 fertilizer was dissolved in water and sprinkled evenly over the soil surface on September 12, 2005 and June 17, 2006, respectively. Dichlorvos ($C_4H_7Cl_2O_4P$) was applied to kill mole crickets (*Scapteriscus borellia* Giglio-Tos) on July 1, 2006 because soil disturbance by these animals was observed, which could result in serious damage to the artificial crusts. These management practices ceased after July, 2006, except for manual weeding, which was performed at regular intervals and lasted until the end of the experiment. The plots with and without artificial crusts were all managed in an identical manner, with respect to irrigation, fertilization, and application of pesticides for soil animals and weed control.

2.4. Measurements

Before the experiment, the topsoil (10 cm) in the plots was sampled and its physiochemical properties were tested. During the experiment, the measurements mainly addressed three parameters over eight years from 2005 to 2012: the coverage of artificial crusts, runoff, and soil water content at different depths. These parameters were measured using the following methods. (1) Photographs of the soil surface were taken at more than five sites in each plot using a digital camera (C2500L, OLYMPUS in Japan), and the coverage of artificial crusts was then calculated from the pictures via supervised classification in ERDAS IMAGINE 8.7 (Xiao et al., 2011b, 2014). (2) The runoff volume (V) from the plots was measured after each rainfall event and then converted to the runoff depth (D) using following equation.

$$D = V/[S \times \cos(arctan\theta)] \tag{1}$$

In this equation, D is the runoff depth, in mm; V is the runoff volume collected from the plots, in L; S is the area of the plot, in m^2; θ is the slope gradient of the plot, in %. (3) Three plastic tubes were installed on the upper, middle, and lower slopes of the plots. Using these tubes, the soil water content at 0–90 cm depths was measured at intervals of 10 cm with a time domain reflectometry probe (TRIME-IPH, IMKO in Germany). The soil water content of each plot was obtained from the mean values of the data from the three tubes in the plot. Additionally, the rainfall during the experiment was also monitored using a standard rain gauge.

2.5. Data analysis

The effects of artificial crusts were determined by the difference in soil water content (θ_E) and soil water storage (W_E) between the artificial crusts and the control, defined as follows.

$$\theta_E(L) = \theta_{BSCs}(L) - \theta_{CK}(L) \quad (2)$$

$$W_E(L) = W_{BSCs}(L) - W_{CK}(L) \quad (3)$$

In these equations, L is the soil depth ranging from 10 to 90 at 10 cm intervals, in cm; $\theta_E(L)$ is the difference of soil water content at L depth between the artificial crusts and the control, in % v/v; θ_{crusts} is soil water content of the artificial crusts at L depth, in % v/v; θ_{CK} is soil water content of the control at L depth, in % v/v; $W_E(L)$ is the difference of soil water storage at L depth between the artificial crusts and the control, in mm; $W_{crusts}(L)$ is soil water storage of the artificial crusts at L depth, in mm; $W_{CK}(L)$ is soil water storage of the control at L depth, in mm. The soil water storage at different soil depths, $W(L)$ in mm, was calculated from the soil water content, $\theta(L)$ in % v/v, using the following equation.

$$W(L) = \sum_{10}^{L} \theta(L)/100 \times 100 \quad (4)$$

The experimental data were analyzed based on descriptive statistics in SPSS 20, and the final results of each treatment averaged from the mean values of the three replications and were expressed as the mean ± standard error. The differences between the artificial crusts and the control were also statistically evaluated at 5% probability level by the repeated measures ANOVA and the paired-samples t test in SPSS 20. The representations and graphical fit of the experimental data were generated using OriginPro 9.1.

3. Results

3.1. Culture of artificial crusts

The complete development process of the artificial crusts from bare soil (Fig. 1A) to full coverage of the plots (Fig. 1L) following the inoculation is clearly reflected in Fig. 1. The artificial crusts in the plots had developed considerably after 301 days (May 13, 2006, see Fig. 1C), which included 168 days in winter, during which their growth was slowed down by low temperature and insufficient moisture. Artificial crusts were very similar to natural crusts in the local environments in both their appearance (including their density, height, and color of moss plants) and species composition (dominated by *Bryum arcticum* (R. Brown) B.S.G. and *Didymodon vinealis* (Brid.) Zander; Fig. 1).

Coverage of artificial crusts had increased significantly ($n = 15$, $F = 49.05$, $P < 0.001$) from zero to 6% at the end of 2005 and subsequently to 63%, 78% and 93% at the end of 2006, 2007 and 2008, respectively (Fig. 2). Cover then remained constant over the next four years. A sharp and significant increase was observed from 12% in May to 64% near October 2006, indicating that the initial development of artificial crusts was rapid, associated with the abundant soil moisture in the rainy season. However, these artificial crusts were patchy rather than uniformly growing over the whole plot. Additionally, no obvious changes were observed after the application of phosphorus and potassium fertilizer. However, the disturbance of soil surface by mole crickets was severe, and the growth of the artificial crusts was very sensitive to these disturbances and the resulting soil burial (Fig. 1C–E). In this study, the mole crickets did not result in serious and detectable reductions on the total crusts coverage because we applied pesticide immediately after we observed them.

3.2. Effects of artificial crusts on runoff

The annual precipitation recorded during the experiment ranged from 324.6 mm to 438.7 mm, averaging to 396.7 mm. A total of 21 runoff events under natural rainfall conditions were recorded (Fig. 3). The plots with the artificial crusts had consistently less runoff than the control during almost every rainfall event ($F = 28.99$, $P = 0.006$). Artificial crusts reduced runoff by 25%, 32%, and 10% in 2006, 2007, and 2008, respectively. In total, artificial crusts reduced runoff by 16.3 mm in absolute terms, and 26.6% in relative terms. However, total runoff of artificial crusts and the control amounted to only 11% and 15%, respectively, of the total rainfall in these three years. Thus although artificial crusts significantly reduced runoff, most (>85%) of the rainfall ultimately infiltrated into soil.

3.3. Effects of artificial crusts on soil water content

The soil water content in the upper 30 cm fluctuated greatly and was closely correlated with rainfall, while the soil water content below 30 cm was more stable (Fig. 4). Due to the impact of rainfall events, the soil water content of the artificial crusts and the control was not consistent over time or at different soil depths. The obtained curves in Fig. 4 could be divided into two stages: a first stage from 2006 to 2007 and a second stage from 2008 to 2012. During the first stage, the soil water content of the artificial crusts was generally higher than that in the control in the upper 50 cm of soil, while the results were reversed at soil depths below 50 cm, especially at 60–70 cm and 80–90 cm. During the second stage, the soil water content of the artificial crusts was obviously and consistently lower than that of the control throughout most of the soil profile, except for 0–20 cm, where the effects of the artificial crusts were influenced and possibly overshadowed by rainfall.

The differences in soil water content between artificial crusts and the control were significant at 10 cm ($F = 6.22$, $P = 0.05$), 70 cm ($F = 7.36$, $P = 0.02$), 80 cm ($F = 6.95$, $P = 0.03$), and 90 cm ($F = 7.78$, $P = 0.01$), but insignificant at the others depths ($P > 0.05$). The soil water content changed significantly along with the time effects ($F > 14.13$, $P < 0.001$) and the time and crust interaction effects ($F > 1.75$, $P < 0.029$). To further evaluate the effects of artificial crusts on soil water content in different years, the six representative dates (corresponding to the earliest measurement and the latest measurement performed in a year) were selected for further analysis, as shown in Table 1. Differences in the soil water content between artificial crusts and the control ranged from −6.2% to 1.8% with an average of −1.6%, while the average in early 2006, and at the end of 2006, 2007, 2008, 2011 and 2012 were −1.1%, −0.6%, −1.6%, −1.7%, −2.7%, and −1.9%, respectively. For soil depth, the differences at 10, 20, 30, 40, 50, 60, 70, 80, and 90 cm were 0.8%, 0.2%, −1.0%, −0.9%, −0.9%, −1.9%, −2.8%, −3.0%, and −4.8%, respectively.

Differences (absolute value) in soil water content between artificial crust and the control increased linearly with time from 2006 to 2012 (Fig. 5A) and with soil depth from 0 to 90 cm (Fig. 5B), which implies that the effects of artificial crusts on soil water

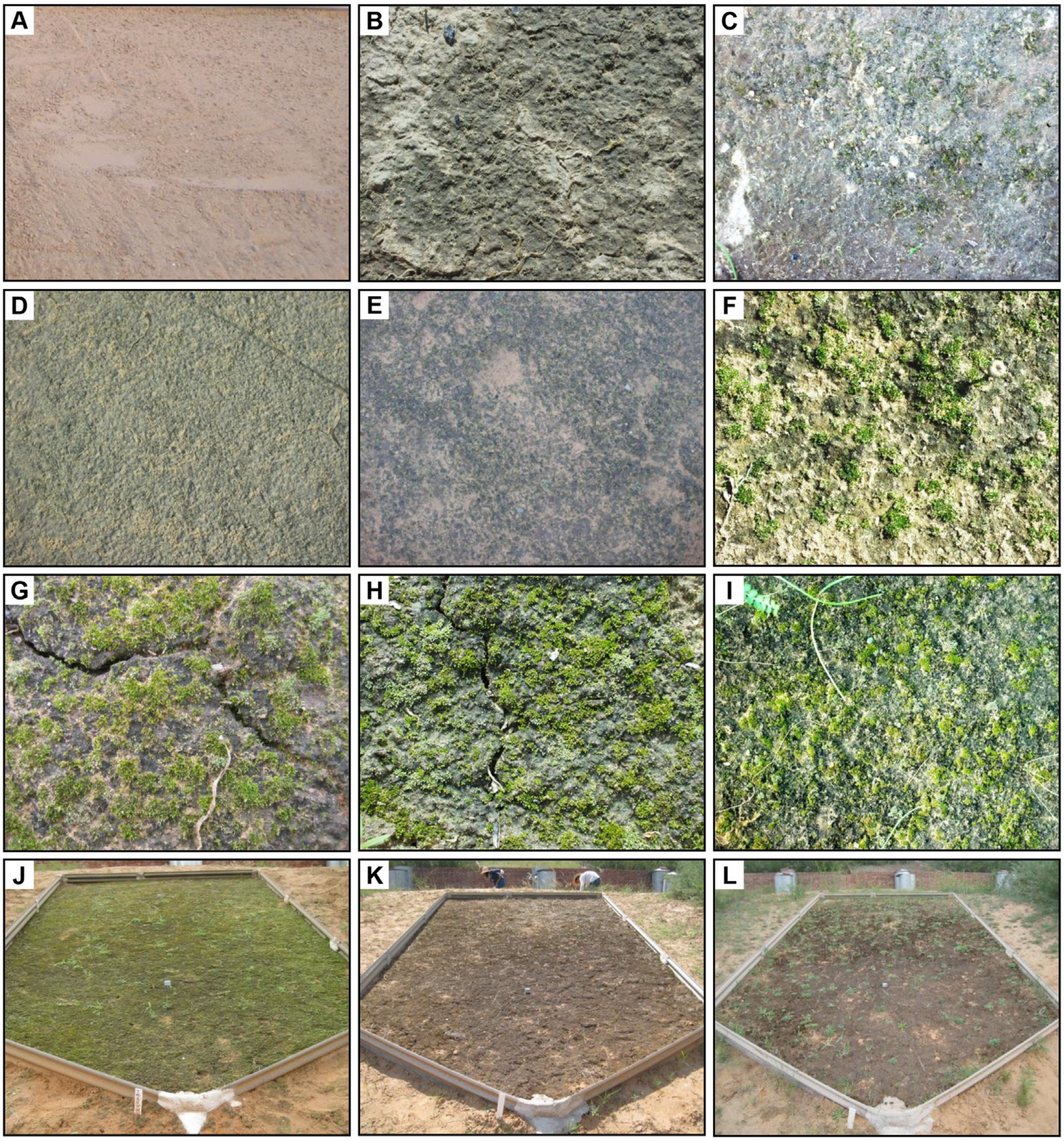

Fig. 1. Development of artificial moss-dominated crusts from zero to nearly full coverage. (A) 2005-8-4, just before the inoculation, (B) 2005-10-13, (C) 2006-5-13, (D) 2006-6-23, (E) 2006-7-19, (F) 2006-8-27, (G) 2006-9-23, (H) 2007-5-22, (I) 2007-7-22, (J) 2008-8-9, (K) 2011-8-2, (L) 2012-5-24.

content increases with time. It also suggests that the effects of artificial crusts on soil water content is greater at depth than on the surface. The reduced effects of artificial crusts on soil water content increased linearly from 5% in the first year to 8% in the last year, with a maximum value of 14% obtained in 2011 (Fig. 5A). Effects of the artificial crusts on soil water content were positive and decreased from 11% at 10 cm depth to 1% at 20 cm, after which the effects became negative, increasing linearly from 5% at 30 cm to 22% at 90 cm (Fig. 5B). These results suggest that artificial crusts slightly increased surface (0–20 cm) soil water content but reduced water content at depth (>30 cm).

3.4. Effects of artificial crusts on soil water storage

The differences of soil water storage between the artificial crusts and the control were generally significant at 10 cm ($F = 8.46$, $P = 0.01$), 80 cm ($F = 5.69$, $P = 0.03$), and 90 cm ($F = 7.01$, $P = 0.02$) but not at other depths ($P > 0.05$). Based on the six representative dates examined in different years (Table 2), the differences in soil water storage between the artificial crusts and the control ranged from −22.3 to −8.1 mm with an average of −14.9 mm, while the differences in early 2006, and at the end of 2006, 2007, 2008, 2011, and 2012 were −11.6, −8.1, −15.9, −15.4, −22.3, and −16.0 mm, respectively.

4. Discussion

4.1. Culture of artificial crusts

Our study confirmed that artificial crusts could develop within two years and be fully formed four years after inoculation. It seems that a longer time was required for the artificial culture of moss-dominated crusts compared with cyanobacteria- or algae-dominated crusts, which may require only a few weeks (Chen et al., 2006; Wang et al., 2009). Moreover, although artificial crusts were well developed, they occurred in patches rather than

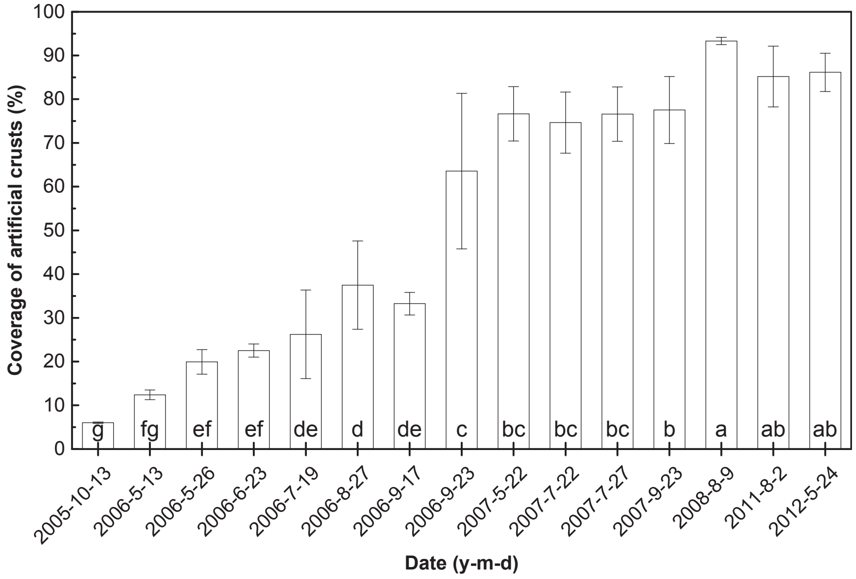

Fig. 2. Changes in coverage of the artificial crusts after inoculation on August 4, 2005. Different letters on the bar indicate significant differences in crusts coverage between these dates at 5% probability level.

uniformly across the plots, possibly due to their location (i.e., center or margin, upper or lower slope), which would be differentially affected by environmental conditions including moisture, solar radiation, temperature, and even wind. In addition, the application of phosphorus and potassium fertilizer did not appear to have obvious positive effects on the development of the artificial crusts in this study, although these nutrients have been described as the two key limiting factors for crusts, particularly moss-dominated crusts (Bowker et al., 2005). Finally, artificial crusts were very sensitive to soil surface disturbances caused by invertebrates and human trampling (Fig. 1C–E). Thus, avoiding disturbance was extremely important for the development of artificial crusts, as proposed by many researchers (e.g., Dojani et al., 2011; Briggs and Morgan, 2012). In fragile ecosystems, this necessity to ensure a stable surface may be more important than inoculation for artificial crusts.

Additionally, artificial crusts in this study were very similar to natural crusts in terms of both their appearance and species composition, but their functions would be possibly very different because the artificial environments including abundant moisture and soil nutrients might alter the characteristics of the artificial crusts and subsequently change their ecological functions (Wu

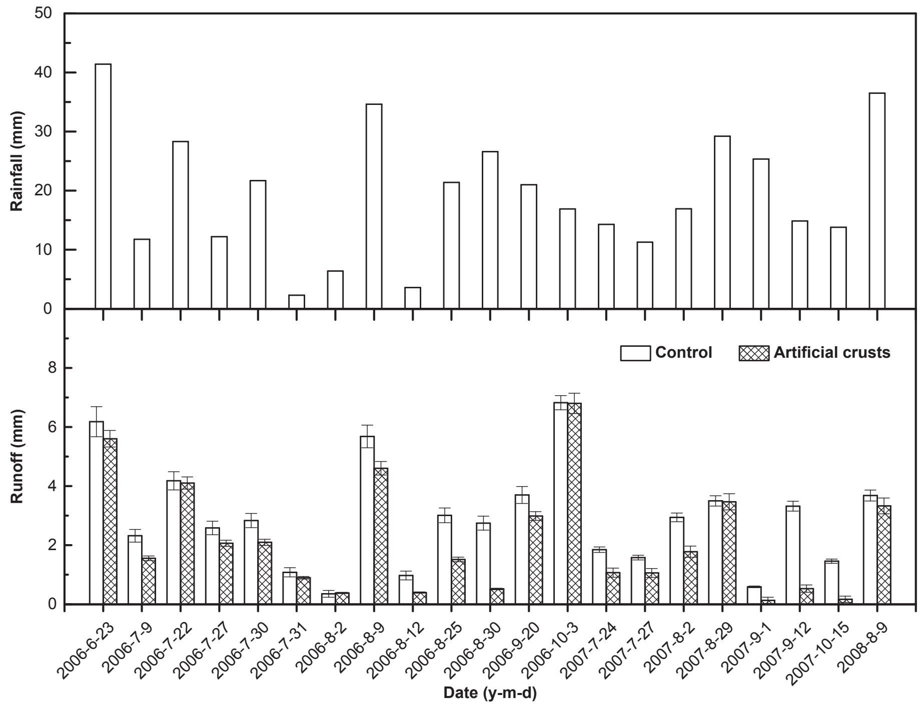

Fig. 3. Corresponding runoff of the artificial crusts and the control during rainfall.

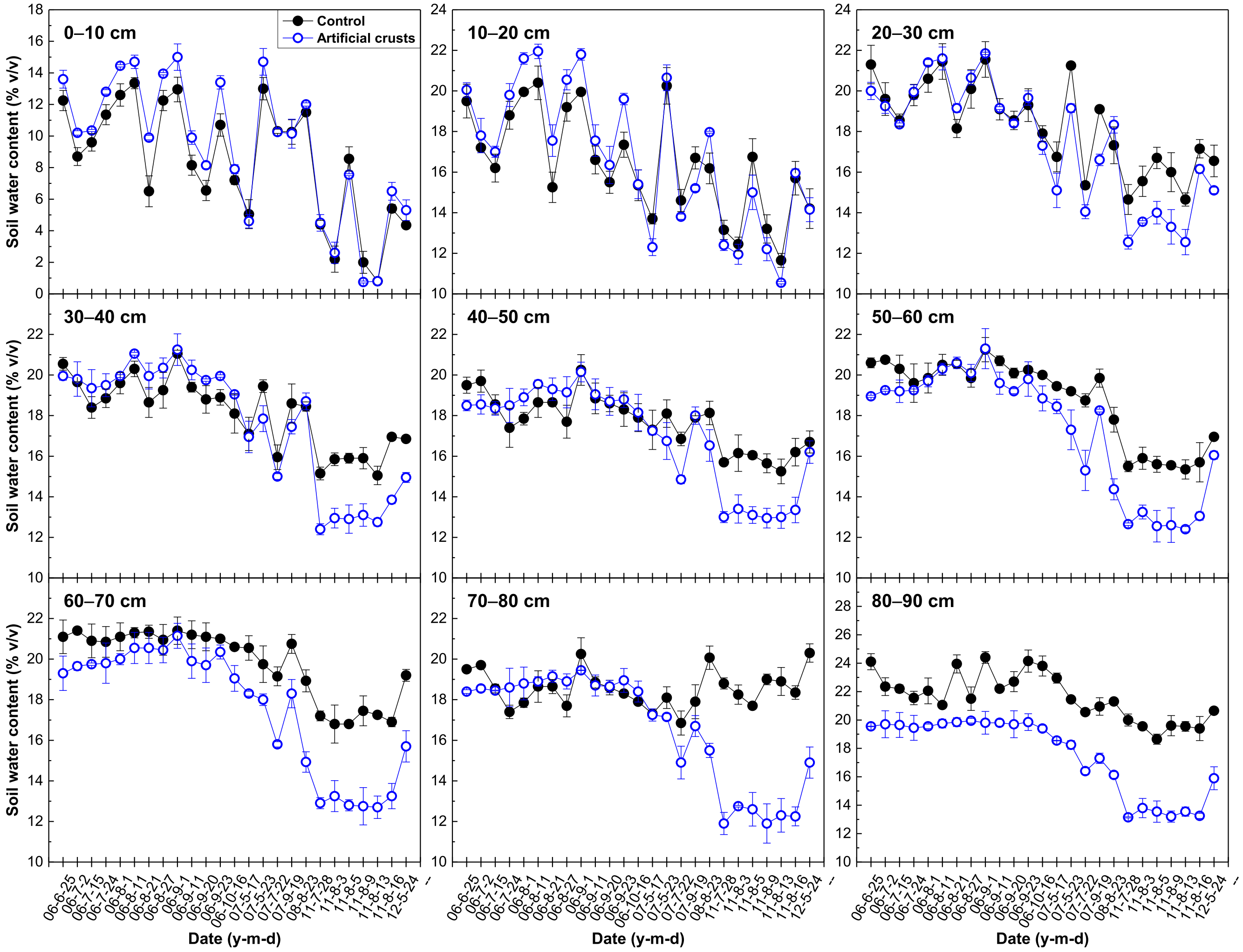

Fig. 4. Changes in soil water content of the artificial crusts and the control at different soil depths.

et al., 2004; Zhang et al., 2005). For example, Bai et al. (2003) reported that the growth of moss in the artificial culture conditions occurred more rapidly than that under natural conditions, and the morphological characteristics of the stems, leaves, and even cells involved in the cultured crusts were significantly different from the natural crusts. Yan and Liu (2003) observed differences in color between the cultured and the natural crusts, reporting that the cultured crusts were mostly green in color, while the natural crusts were usually of a dark/black color.

4.2. *Effects of crusts on runoff*

Artificial moss-dominated crusts reduced total runoff by 16.3 mm in absolute terms and 27% in relative terms compared with the control. This result is consistent with the findings of Kidron et al. (2003), who observed a significant reduction of runoff in sand dunes of the Negev Desert once the moss-dominated crusts were established. Xiao et al. (2011b) also showed that artificially propagated moss-dominated crusts significantly increased

Table 1
Differences in soil water content (% v/v) between the artificial crusts and the control.

Soil depth (cm)	2006-6-25			2006-10-16			2007-9-19			2008-8-23			2011-8-16			2012-5-24		
	Mean	SE[a]	*P*	Mean	SE	*P*	Mean	SE	*P*	Mean	SE	*P*	Mean	SE	*P*	Mean	SE	*P*
0–10	1.35	0.49	0.011*	0.70	0.64	0.385	−0.10	0.69	0.915	0.50	0.15	0.256	1.10	0.69	0.253	0.95	0.43	0.046*
10–20	0.55	1.01	0.631	0.05	0.84	0.958	−1.50	0.98	0.266	1.78	0.15	0.258	0.25	0.07	0.826	−0.05	0.90	0.974
20–30	−1.30	0.19	0.614	−0.60	0.96	0.789	−2.50	0.96	0.331	1.02	0.99	0.912	−1.00	0.33	0.536	−1.45	0.99	0.542
30–40	−0.60	0.25	0.820	0.95	0.45	0.732	−1.15	0.76	0.586	0.25	0.99	0.910	−3.10	0.21	0.046*	−1.90	0.79	0.403
40–50	−1.00	0.31	0.707	0.25	0.28	0.918	0.10	0.25	0.969	−1.59	0.71	0.337	−2.85	0.84	0.007**	−0.50	0.81	0.599
50–60	−1.65	0.57	0.590	−1.15	0.74	0.720	−1.60	0.19	0.546	−3.43	0.71	0.335	−2.65	0.72	0.008**	−0.90	0.58	0.266
60–70	−1.80	0.81	0.046*	−1.55	1.01	0.269	−2.45	0.72	0.007**	−4.00	0.40	0.048*	−3.65	0.47	0.032*	−3.50	1.15	0.004**
70–80	−1.10	0.14	0.048*	0.50	0.28	0.218	−1.20	1.12	0.328	−4.57	0.37	0.044*	−6.10	0.46	0.006**	−5.40	1.10	0.009**
80–90	−4.55	0.82	0.030*	−4.40	0.85	0.040*	−3.65	1.67	0.424	−5.17	0.48	0.042*	−6.15	0.95	0.003**	−4.75	1.99	0.040*

[*] Differences between the artificial crusts and the control are statistically significant at the 5% probability level.
[**] Differences between the artificial crusts and the control are statistically significant at the 1% probability level.
[a] SE is standard error.

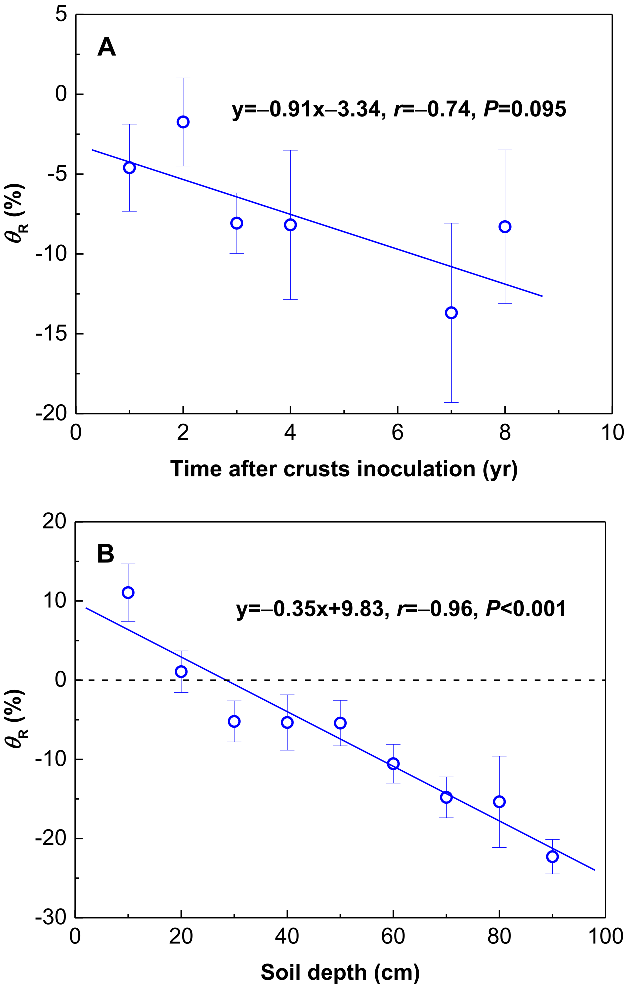

Fig. 5. Relative difference of soil water content (θ_R) changed with time (A) and soil depth (B). The relative difference (θ_R) was equal to the absolute difference (θ_E) of the artificial crusts divided by soil water content of the control (θ_{CK}).

infiltration, which was positively correlated with crust cover. However, increased runoff due to crusts has also been widely reported, possibly due to the differences in crust types or climatic conditions. For example, Kidron et al. (2012) observed higher runoff in crusted plots in the Sevilleta National Wildlife Refuge compared with crust-scalped plots within the northern Chihuahuan Desert in New Mexico, USA. Malam Issa et al. (2011) reported higher runoff coefficients where crusts had developed on erosion crusts compared to structural crusts, and suggested that separating crusts according to the type of the underlying physical crust could explain the contradictory findings related to their role in infiltration and runoff generation. Malam Issa et al. (2009) concluded that the runoff obtained on densely-covered surfaces was significantly higher than on surfaces with thin crusts due to the geometry of the microbial-originated pore system and its functioning. In addition, Belnap (2006) reviewed the influence of crusts on water infiltration and runoff in various global drylands and showed that crusts in hyper-arid regions reduced infiltration and increased runoff, displayed mixed effects in arid regions, and increased infiltration and reduced runoff in semi-arid cool and cold dry lands. Based on the contradictory results reported above, we speculated that the functions of crusts in runoff generation were firstly determined by the crust type and secondly by climatic conditions. However, the functions of crusts in the partitioning of rainfall and runoff may not be as important as generally expected because runoff usually only accounts for a small proportion of rainfall in arid and semi-arid environments.

4.3. *Effects of crusts on soil water content*

In addition to reducing runoff and increasing infiltration, artificial crusts slightly increased surface soil water content but reduced soil water content at depth. A possible reason for this is that artificial crusts adsorbed more water in surface soil layers, which evaporated rapidly after rainfall (Xiao et al., 2010, 2014). As a result, artificial crusts reduced the amount and depth of water infiltration into deeper layers (Almog and Yair, 2007). This explanation is supported by Wang et al. (2006), who reported that the water-holding capacity of crusts was three to nine-times that of shifting dune sand. Another possible reason is that the burrowing of soil animals (e.g., earthworms, ants) resulted in preferential flows, which greatly improved surface soil water content, but altered deep soil water content little. Similar results regarding the effects of natural crusts on soil water content have been reported by other researchers. For example, Kidron and Vonshak (2012) monitored the soil moisture profile of crusts at a 0–40 cm depth over two years and consistently found that crusts not only had a greater moisture but that this moisture was available for longer, more than one month, compared with a nearby site without crusts. Coppola et al. (2011) reported that crusts always caused lower unsaturated soil water fluxes in the sand beneath the crusted layer but had no effect on the local soil water regimes, particularly at depth. Gao et al. (2010) showed that soil water content profiles were affected by crusts. Thus soil water content was higher in the surface if crusts were present. For deeper soil layers, however, soil water content was lower if soils had crusts.

Table 2
Differences in soil water storage (mm) between the artificial crusts and the control.

Soil depth (cm)	2006-6-25			2006-10-16			2007-9-19			2008-8-23			2011-8-16			2012-5-24		
	Mean	SE[a]	*P*	Mean	SE[a]	*P*	Mean	SE[a]	*P*	Mean	SE[a]	*P*	Mean	SE[a]	*P*	Mean	SE[a]	*P*
0–10	1.35	0.49	0.011*	0.70	0.64	0.385	−0.10	0.69	0.915	0.50	0.15	0.256	1.10	0.69	0.253	0.95	0.43	0.046*
0–20	1.90	1.60	0.330	0.75	1.55	0.661	−1.60	1.90	0.444	3.57	1.98	0.260	1.35	1.05	0.519	0.90	2.30	0.561
0–30	0.60	1.40	0.883	0.15	0.95	0.969	−4.10	1.30	0.378	5.35	2.43	0.466	0.35	0.35	0.920	−0.55	0.75	0.887
0–40	0.00	0.30	1.000	1.10	0.20	0.867	−5.25	1.35	0.433	4.07	0.92	0.584	−2.75	1.45	0.590	−2.45	1.85	0.679
0–50	−1.00	1.30	0.915	1.35	1.15	0.884	−5.15	1.25	0.570	5.08	0.62	0.947	−5.60	1.90	0.390	−2.95	0.25	0.668
0–60	−2.65	1.75	0.831	0.20	1.90	0.986	−6.75	2.05	0.565	−2.80	0.32	0.837	−8.25	0.15	0.295	−3.85	1.25	0.615
0–70	−4.45	0.15	0.740	−1.35	0.65	0.920	−9.20	1.30	0.476	−3.27	1.47	0.657	−11.90	1.70	0.246	−7.35	2.25	0.439
0–80	−5.55	1.45	0.459	−0.85	1.70	0.632	−10.40	1.90	0.219	−11.93	1.57	0.547	−18.00	1.90	0.042*	−12.75	1.35	0.049*
0–90	−11.57	1.30	0.228	−8.05	1.50	0.336	−15.91	1.55	0.007**	−15.37	1.87	0.464	−22.31	0.25	0.005**	−16.01	2.90	0.002**

*Differences between the artificial crusts and the control are statistically significant at the 5% probability level.

**Differences between the artificial crusts and the control are statistically significant at the 1% probability level.

[a] SE is standard error.

Although we found reductions in soil water for soils below 30 cm when crusts were present, we cannot conclude that the hydrological and ecological functions of artificial crusts are negative. Firstly, we only evaluated the hydrological functions of artificial moss-dominated crusts, while other types of artificial crusts, such as those involving algae and lichen, may exhibit different hydrological functions in terms of infiltration and evaporation. Secondly, this study only involved a small plot-scale experiment in a specific climatic environment, and artificial crusts may exhibit different hydrological functions under other climate conditions. Thirdly, the decrease in deep soil water content was also possibly caused by the water utilization of the mosses in the artificial crusts. If the mosses are using and transpiring this water, the consequences could be positive in terms of carbon exchange and carbon and organic matter input to the soil (Douma et al., 2007). The fact that the mosses are reducing soil water content may indicate that other processes are operating, that water is used for carbon and nitrogen fixation, which could balance any negative effects on deeper soil water. Thus artificial crusts might have positive effects on other ecological functions such as soil carbon and nitrogen sequestration (Green et al., 2008; Chamizo et al., 2012b), soil protecting (Rodríguez-Caballero et al., 2012; Tisdall et al., 2012) and habitat amelioration for plants, animals and microbes (Xiao et al., 2013). The importance of artificial crusts should be evaluated in terms of multiple ecological functions. Further studies that address the different functions performed by different artificial crusts is clearly warranted.

5. Conclusions

Our results indicate that it is feasible to artificially culture moss-dominated crusts for soil stabilization and water conservation purposes. However, artificial crusts only slightly improved surface soil water conditions and greatly impaired deeper soil water conditions, which might exacerbate the poor soil water conditions in desertified environments. Our results would be helpful for understanding the ecological and hydrological functions of artificial crusts, and provide useful information on the potential use of these crusts for soil and water conservation and to reduce desertification in semi-arid ecosystems.

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