Artificial culture of biological soil crusts and their effects on runoff and infiltration under simulated rainfall on the Loess Plateau of China

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Abstract
On the Loess Plateau of China, biological soil crusts were artificially cultured in the laboratory, and then its effects on runoff and infiltration were studied under simulated rainfall. The results showed that (1) it was feasible to artificially culture biological soil crusts dominated by moss in the laboratory, and biological soil crusts inoculated by sprinkling crushed fragments of stems and leaves of natural biological soil crusts would almost completely cover the soil surface after about 15 months; (2) The artificially cultured biological soil crusts would significantly increase infiltration and subsequently decrease runoff, and the effects were positively linearly correlated to the surface coverage by biological soil crusts; (3) the effect of slope gradient on the partition of water between infiltration and runoff on biological soil crusts was similar to bare soil, but it seems that the effects of biological soil crusts in increasing infiltration and decreasing runoff may be more effective on steep slopes than on gentle slopes; (4) the start time of the runoff process was delayed by the presence of biological soil crusts, and also the soil-water redistribution process of biological soil crusts is significant than that of bare soil. These results may be useful for helping to control desertification by biological soil crusts in the Loess Plateau of China or similar regions.

Key Words
Soil and water loss; soil hydrology; desertification control; harsh environments

Introduction
Drought, concentrated rainfall, loose particles of loess soil, complex landform and long-term improper land use interact with each other on the Loess Plateau of China, and result in very sparse vegetation and consequently the most serious water loss and soil erosion (Cha and Tang 2000). However, the biological soil crusts (BSCs), which are defined as a complex mosaic of soil, cyanobacteria, green algae, lichens, mosses, microfungi and other bacteria by Belnap and Lange (2003), are extensively distributed under the shadow or between the sparse vegetation (Zhao *et al.* 2006). However, the ecological functions of these crusts are not clear. The serious soil-water loss, extensively distribution and potential important functions of biological soil crusts in soil and water conservation (Eldridge 1993; Belnap *et al.* 2005) imply that these crusts may play a critical role in the remediation and restoration of fragile ecological environment on the Loess Plateau of China. The objectives of this research were to (1) evaluate the prevalent artificial culture method of biological soil crusts on the Loess Plateau of China, (2) describe the preliminary differences between artificial cultured biological soil crusts and natural crusts in appearance and composition, and (3) quantitatively assess the influences of artificial cultured biological soil crusts on infiltration and runoff.

Methods
Artificial culture of biological soil crusts
The loess soil was collected and sifted through a sieve with 10 mm diameter. Then the prepared soil was packed into 8 boxes (1.0 m× 0.4 m× 0.4 m) by 1.3 g/cm^3. Afterward, the natural biological soil crusts collected from field were crushed and mixed with some fine soil, and seeded uniformly (inoculation dose of air dry matter is 1.25 kg/m^2). The simulated rainfall experiment was started when the cultured biological soil crusts were initially formed. The rainfall intensity and duration were as applied at 50 mm/h for 1 or 1.5 hours, respectively. In this study, nntwo factors including coverage of crusts (bare soil and biological soil crusts with different coverage at different growth days) and slope gradient (9%, 18%, 27%) were considered. The simulated rainfall was repeated 3 times in 376 days (trial a), 414 days (trial b) and 448 days (trial c) after the inoculation of biological soil crusts.

Measurement and data analysis
The coverage of biological soil crusts in boxes was calculated from the pictures that were obtained by a high

resolution camera by Supervised Classification in Erdas Imagine 8.7, and then validated and corrected on the basis of personal experience (Pan and Shangguan 2005). In the simulated rainfall experiment, the runoff from every soil box was collected and measured every 2 minutes from starting point to the end. The soil water profile was also measured before, after and about 24 hours after rainfall respectively by TDR (TRIME-EZ, IMKO in Germany) at interval of 5 cm. The coverage of biological soil crusts was classified by K-Means Cluster in SPSS 15.0 for Windows. The different classes imply different treatments for the coverage of biological soil crusts. The experimental data were analyzed using Descriptive Analysis and one-way ANOVA by SPSS 15.0.

Results

Relationship between runoff-infiltration and coverage of biological soil crusts

According to the classification results of the coverage of biological soil crusts, 8 soil boxes can be classified to 3 classes in trial a (No. 1, 2 for bare soil; No. 3, 4, 5, 6 for biological soil crusts averaging coverage 29.12%, labelled 29% BSC; No. 7, 8 for biological soil crusts averaging coverage 60.97%, labelled 61% BSC), and also 3 classes in trial b (No. 1, 2 for bare soil; No. 3, 5 for biological soil crusts averaging coverage 40.01%, labelled 40% BSC; No. 4, 6 7, 8 for biological soil crusts averaging coverage 78.17%, labelled 78% BSC). Statistic analysis by one-way ANOVA show that there are significant differences among these 3 classes ($F=95.520$, $P\leqslant 0.001$ for trial a; $F=19.537$, $P=0.012$ for trial b). Therefore, 8 soil boxes can be regarded as 3 treatments (bare soil, 29% BSC and 61% BSC in trial a; bare soil, 40% BSC and 78% BSC in trial b).

The cumulative runoff during simulated rainfall in trial a and trial b were presented in Figure 1. In trial a, the entire runoff process was delayed about 10 minutes by the presence of the biological soil crusts from the comparable results of start time at initial stage (about 20 minutes for bare soil and 30 minutes for 29% BSC) and steady state (about 38 minutes for bare soil and 49 minutes for 29% BSC). However, this effect was not clear in trial b, possibly due to the 9% slope gradient and the relative higher initial soil water content that was the result of rainwater infiltration in trial a. The experimental data from the steady state was linearly fitted ($y=ax+b$), and parameter a, which from the slope gradient of the fit line was equal to the steady runoff rate listed in Table 1. Also, the comparable results of the runoff coefficients, which is the percentage of total runoff to total precipitation, show that the runoff coefficient was decreased 33.33% by 29% BSC and 100% by 61% BSC in trial a, decreased 41.79% by 40% BSC and 59.70% by 78% BSC in trial b.

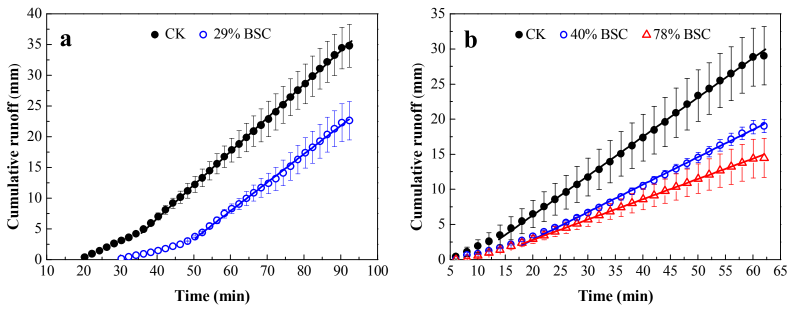

Figure 1. Cumulative runoff versus time during the trial a (a) and trial b (b).

Table 1. Total precipitation, infiltration, runoff, steady runoff rate and runoff coefficient of trial a and trial b.

	Trial a			Trial b		
	Bare soil	29% BSC	61% BSC	Bare soil	40% BSC	78% BSC
Precipitation (mm)	75.62[a]	74.51[a]	67.22[b]	45.37[a]	49.89[a]	48.98[a]
Runoff (mm)	34.46[a]	22.28[a]	0.00[b]	29.03[a]	19.62[ab]	14.47[b]
Steady runoff rate (mm/min)	0.55[a]	0.46[b]	0.00	0.56[a]	0.39[a]	0.29[a]
Infiltration (mm)	41.18 [b]	52.24[ab]	67.22[a]	16.34[b]	30.27[a]	34.51[a]
Runoff coefficient	0.45[a]	0.30[a]	0.00[b]	0.67[a]	0.39[b]	0.29[b]

The different letter in same row means it has significant differences at 5% probability level

The soil moisture profile measured before and after rainfall in trial a and trial b are presented in Figure 2. The infiltration depth can be easily inferred from the intersection of soil moisture profiles. This infiltration depth is 25 cm for bare soil, 30 cm for 29% BSC, far more than 30 cm (which is the maximum of monitoring depth) for 61% BSC in trial a, and 20 cm for bare soil, much more than 30 cm for biological soil crust (both for 40% BSC and 78% BSC) in trial b. It indicates that the infiltration depth was significantly increased by the biological soil crusts. In other words, the infiltration was encouraged by the presence of biological soil crusts. Except for infiltration depth, the amount of infiltration water could also be calculated from the soil moisture profile. It should be noted that the total infiltration determined from soil moisture is in agreement with the infiltration, which is subtracted total runoff from total precipitation according to the principle of water balance. This result implies that TRIME-EZ has good accuracy and precision in the measurement of soil moisture.

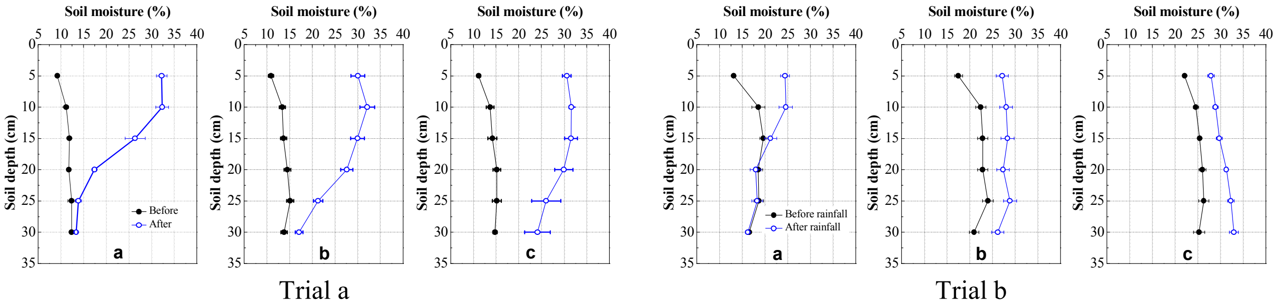

Figure 2. Soil moisture profile before and after rainfall in trial a (a. bare soil, b. 29% BSC and c. 61% BSC) and trial b (a. bare soil, b. 40% BSC and c. 78% BSC). The infiltration depth can be determined from the intersection of soil moisture profiles.

Relationship among runoff-infiltration, slope gradient and presence of biological soil crusts

In trial c, the biological soil crusts almost completely covered the soil surface in each soil box. Thus the coverage of cultured biological soil crusts in each soil box was considered to be 100%. So another critical factor, slope gradient, which largely decides the partition between infiltration and runoff during rainfall was studied instead of coverage of biological soil crusts.

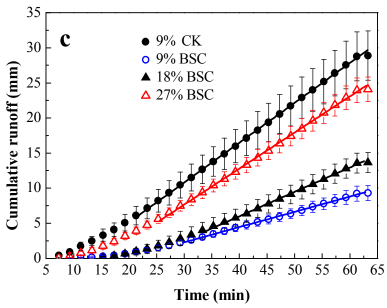

Figure 3. Cumulative runoff verses time during the trial c. The coverage of biological soil crusts in here is almost 100%, and the percentage in legend means the slope gradient.

From Figure 3 and Table 2, we can find that the runoff coefficient was largely decreased 67.24% by biological soil crusts as compared to bare soil. Also, the runoff coefficient of biological soil crusts is increased 36.84% at 18% slope gradient, and increased 136.84% at 27% slope gradient as compared to that at 9% slope gradient. However, the runoff coefficient of biological soil crusts increased 36.84% when the slope gradient increasing from 9% to 18%, and increased 73.08% when the slope gradient increasing from 18% to 27%. This trend of runoff coefficient changing with slope gradient may imply that the protection of biological soil crusts may be more effective under steep slope conditions than gentle slope conditions.

Table 2. Total precipitation, infiltration, runoff, steady runoff rate and runoff coefficient of trial c. The coverage of biological soil crusts in here is almost 100%, and the percentage in legend means the slope gradient

	9% bare soil	9% BSC	18% BSC	27% BSC
Precipitation (mm)	50.08^{a}	50.12^{a}	51.62^{a}	54.04^{a}
Runoff (mm)	28.90^{a}	9.30^{b}	13.66^{b}	24.08^{a}
Steady runoff rate (mm/min)	0.57^{a}	0.22^{b}	0.35^{b}	0.51^{a}
Infiltration (mm)	21.19^{c}	40.82^{a}	37.96^{a}	29.97^{b}
Runoff coefficient	0.58^{a}	0.19^{c}	0.26^{c}	0.45^{b}

From the soil moisture profile before and after trial c, we can also infer that the infiltration depth is about 15 cm for bare soil with 9% slope gradient, 25 cm for biological soil crusts with 27% slope gradient, 30 cm for biological soil crusts with 18% slope gradient, and more than 30 cm for biological soil crusts with 9% slope gradient. It implies that infiltration was largely increased by biological soil crusts and decreased by slope gradient. In trial c, the soil moisture profile was also measured 18 hours after the rainfall in order to evaluate the differences of soil water redistribution process among the 4 treatments as the soil water redistribution process is a very important way which can be used to evaluate the water holding capacity of soil. Finally we found that the soil water redistribution process of biological soil crusts is significant than bare soil. Thus we can conclude that the soil water redistribution process may be largely affected by biological soil crusts.

Conclusion

All collected experimental data was used to analysis the correlation among runoff coefficient, slope gradient and coverage of biological soil crusts. The histogram, P-P plot and partial regression plot in linear regression results unanimously confirm that the variables satisfied linear distribution, and prove that the regression function passed the test for homogeneity of variance. The resulting regression function is $y=1.278x_1-0.417x_2+0.490$ ($F=12.547$, $P<0.001$, x_1 is slope gradient, x_2 is coverage of biological soil crusts, and y is runoff coefficient). From the regression function, we can find that the runoff coefficient is positive to slope gradient and negative to coverage of biological soil crusts. If we only consider the effects of biological soil crusts, we can get a good linear relationship between the coverage of biological soil crusts and decreased runoff (Figure 4). The correlation coefficient ($r=0.9737$) suggests that this linear relationship is statistically significant at 1% probability level (the critical value of r at 1% probability level is 0.7980).

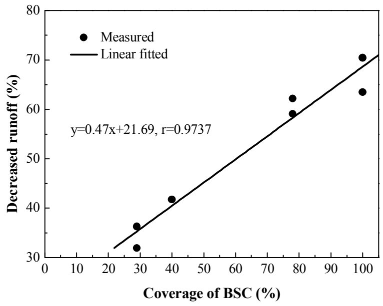

Figure 4. Linear relationships between coverage of biological soil crusts and decreased runoff.

From the three simulated rainfall experiment we can conclude that: (1) it is feasible to artificially culture biological soil crusts dominated by moss in laboratory, and biological soil crusts inoculated by sprinkling crushed fragments of stems and leaves of natural biological soil crusts will almost completely cover the soil surface after about 15 months; (2) the artificial cultured biological soil crusts will significantly increase infiltration and subsequently decrease runoff, and the effects is positively linearly correlated to the coverage of biological soil crusts; (3) the effects of slope gradient on the partition between infiltration and runoff on biological soil crusts is similar to bare soil, but it seems that this effects of biological soil crusts in increasing infiltration and decreasing runoff may be more effective for steep slope than gentle slope; (4) the start time of the runoff process was delayed by biological soil crusts, and also the soil water redistribution process of biological soil crusts is clearer than for bare soil.

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