# Runoff and Soil Loss from Revegetated Grasslands in the Hilly Loess Plateau Region, China: Influence of Biocrust Patches and Plant Canopies

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**Abstract:** Biological soil crusts (biocrusts) cover up to 60–70% of the soil surface in grasslands rehabilitated since the Grain for Green project was implemented in the hilly Loess Plateau region in 1999, which exerted significant impacts on runoff and soil loss from revegetated grasslands. In the study, field plots were used to investigate runoff and soil loss in sites of a 4- and a 13-year revegetated grassland, with each exhibiting an early and a later successional biocrust, respectively. The objectives of the study were to (1) examine the role of biocrusts on runoff and soil loss during their early and later successional stages in a semiarid region under water erosion, (2) determine the influence of biocrusts on soil antiscourability with different runoff intensities, and (3) isolate the effects of biocrust patches and vascular plant canopies on runoff and soil loss from revegetated grasslands. Treatments used in both sites included (1) retaining biocrusts and plant canopies intact (CP), (2) retaining biocrusts without plant canopies (CNP), (3) retaining plant canopies without biocrusts (PNC), and (4) removing both biocrusts and plant canopies (NCP). The simulated scouring water flux was designed as 7.8, 12.0, and 16.0 $\mathrm{L \cdot min^{-1}}$ to reflect local rainfall conditions. The results indicated that the runoff yield was increased by biocrust patches in their well-development stage. Runoff was increased by 15.1% when plant canopies were retained and 16.0% when plant canopies were removed in the 13-year revegetated grassland with the 12.0 $\mathrm{L \cdot min^{-1}}$ scouring water flux. Compared with biocrust patches, plant canopies reduced runoff by 11.3% (with biocrusts) and 8.4% (biocrusts was removed) with the same scouring water flux. No significant difference was found in runoff yield with respect to the four treatments in the 4-year revegetated grassland. In contrast, 92% of the sediments were reduced for the formation of biocrusts in their early successional stage (cyanobacteria-dominated biocrusts) in the 4-year revegetated grassland with respect to CNP compared with NCP at the 12.0 L/min scouring intensity. No sediment was generated on either CP or CNP treatments in grassland revegetated for 13 years (moss-dominated biocrusts) with the same intensity of simulated runoff. Compared with biocrusts, plant canopies had a limited influence on soil loss. This amounted to reductions of 45 and 10% in soil loss for grasslands that revegetated for 4 and 13 years, respectively. The results of the study suggest that biocrusts play an important role in soil loss control from water erosion in semiarid regions, although there was a potential increase in runoff yield. **DOI:** 10.1061/(ASCE)HE.1943-5584.0000633. *© 2013 American Society of Civil Engineers.*

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## Introduction

Biological soil crusts (biocrusts), which are intimate associations between soil particles and lichens, mosses, fungi, cyanobacteria, eukaryotic algae, and other heterotrophic bacteria that live within or on the very top of soil surface in differing proportions (Rosentreter et al. 2008), have been found almost all over the world and in all climatic regions, especially in arid and semiarid regions. The percent coverage of biocrusts may be 70% in such regions (Belnap et al. 2003), which play several critical roles in arid and semiarid ecosystems, such as increasing soil stability, inhibiting or promoting surface water infiltration, influencing soil moisture evaporation, and improving soil properties, e.g., fertility, texture, and so on (Greene et al. 1990; Eldridge and Greene 1994; Evans and Johansen 1999; Eldridge et al. 1999, 2000; Belnap 2006).

As a kind of living surface cover, biocrusts can improve soil capacity to resist erosion from wind and water. Studies have demonstrated that soil losses can be reduced through the development of biocrusts in some ecosystems (Belnap 2003; Leys and Eldridge 1998; Belnap et al. 2007; Eldridge and Leys 2003; Zhang et al. 2006; Guo et al. 2008). In relation to wind erosion, studies showed soil threshold friction velocity (TFV) increases significantly when biocrusts were presented (Evans and Johansen 1999; Belnap 2003; Belnap and Gillette 1998; West 1990; Eldridge et al. 2000). Although only a few studies have been conducted on the impacts of biocrusts on soil water erosion, these studies had similar conclusions, i.e., that soil losses were cut down greatly with the development of biocrusts. In 1990, Kinnell et al. (1990) found that sediment yield was reduced by 3–5 times for the presence of biocrusts compared with depositional crusts. Moreover, Eldridge and Greene (1994) reported a strong positive relationship between coverage of biocrusts and splash erosion in the absence of vascular cover.

Whereas the process of biocrusts development is well understood, the capacity of biocrusts to affect soil capacity to resist wind

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and water erosion during different successional stages has not been investigated. Furthermore, the capacity of biocrusts to protect soil against water erosion in comparison with vascular plants has also not been investigated. Vascular plants are commonly regarded as the most important biological factor influencing soil and water losses in many regions of the world (Morgan 1986). However, vascular plant cover in revegetated grasslands in the hilly Loess Plateau is often sparse and distributed in a mosaic of vegetated patches or isolated plants. Biocrusts often occur extensively in the interspace of vascular plants. Therefore, it would be more appropriate to note that the magnitude of runoff yield and soil loss from grasslands with both plants and biocrusts patches is actually the result of the development and presence of both. However, few studies to date have focused on the differential contributions of these two components on soil loss and runoff yield.

Soils in the Loess Plateau region of China, with its deep, loose loess (a loamy Eolian deposit), is extremely erodible, fragile, degraded, and continuously losing its productivity because of severe water erosion (Xu et al. 2006a, b; Ni et al. 2008). Additionally, soil erosion with a module of more than $10,000\ \mathrm{Mg\,km^{-2}\,year^{-1}}$ used to be a serious ecological issue in the region (Liu 1999). Being aware of the extent and severity of the problem, since 1999, the Chinese government has promoted an ecological project termed Grain for Green that aimed to rehabilitate the degraded ecosystems through vegetation restoration in the western regions of China, including the Loess Plateau region (Peng et al. 2007; Feng et al. 2005). The major approach of the Grain for Green project was converting low-yielding farmlands on slopes of 25° or more back into forest or pasture lands. Biocrusts formed and developed relatively quickly on soil surfaces in the abandoned slopes with vascular plant succession, attributable to the reduced disturbance from humans. In the hilly Loess Plateau region, biocrusts formed on the soil surface in the first year following cropland abandonment and only a further 8–10 years were necessary for biocrusts to achieve a high level of stability, with a coverage of 70–80% (Zhao et al. 2006a; Zhang et al. 2007). Given the extensive distribution of biocrusts and their importance in ecological function, recent research has been conducted on the ecological function of biocrusts in the hilly Loess Plateau region. The chief studies demonstrated that biocrusts in the region are dominated by cyanobacteria, green algae, and bryophytes. Soil fertility and cohesion of the revegetated grassland were improved greatly following biocrusts formation (Zhao et al. 2006a). However, limited work has been conducted on runoff yield and soil loss response with the changing coverage and succession of biocrust layers.

Following a survey of the development and distribution of biocrusts in the region, the authors postulated that biocrusts may have a comparable or greater influence on runoff yield and soil loss than vascular plants in the region, particularly considering their large area extent and their effect on soil structure (Gaskin 2001; Zhao et al. 2006b; Knapen et al. 2007). The authors' research proposed to conduct field experiments using a scouring simulation method on plots in two revegetated grasslands, which represented an early and a late successional stage of biocrusts. The chief purposes of the research were to (1) examine the role that biocrusts play on runoff yield and soil loss during their different successional stages in a semiarid region with water erosion, (2) determine the influence of biocrusts on soil antiscourability with different runoff quantities, and (3) isolate the effects of biocrusts patches and vascular plants canopies on runoff and soil loss from revegetated grasslands. The authors define CP, CNP, and PNC to be biocrusts with plant canopies, biocrusts without plant canopies, and plant canopies without biocrusts, respectively. The results will be meaningful in understanding the ecological function of biocrusts and helpful for evaluating results of the Grain for Green ecological program in the study region.

## Materials and Methods

### Site Description

The research was conducted on revegetated grasslands at the Ansai Soil and Water Conservation Research Station of the Chinese Academy of Sciences. The station is located on a typical hilly Loess Plateau landscape in northern Shaanxi province, China (latitude 36°51″ N; longitude 109°19″). The mean altitude of the research station is approximately 1,200 m, but topographic variations are significant within the hill and gully landforms.

The climate of the region is a typical semiarid continental climate, with an average annual temperature of 8.8°C. Mean monthly temperatures ranged from 22°C in July to −7°C in January. Average annual precipitation was approximately 500 mm, with 60% falling between July and September. Accumulated temperatures above 0 and 10°C were 3,733 and 3,283°C, respectively. On average, there were 157 frost-free days and 2,415 hours of sunshine annually.

The average thickness of the loess parent material is approximately 50—80 m, with uniform soil texture of *Calciustepts*. The soil was highly susceptible to erosion, with annual loss rates of $10,000–12,000\ \mathrm{Mg\,km^{-2}\,year^{-1}}$ before 1999 (Liu 1999).

Common zonal vegetation in the research region included species such as *Cotoneaster horizontalis* Dcne., *Rosa xanthina* Lindl., *Rubus parvifolius* Linn., *Sophara viciifolia* Hance., *Bothriochloa ischaemum* (Linn.) Keng, *Stipa bungeana* Trin, *Artemisia sacrorum* Ledeb., *Artemisia capillaris* Thunb., and *Artemisia giraldii* Pamp.

### Scouring-Runoff Plots

The authors' scouring experiments were conducted on two revegetated grasslands that had not been cultivated for 4 and 13 years, respectively. The characteristics of the two study sites are displayed in Table 1.

Both sites of the experiment developed a homogeneous cover of biocrusts and plants. The plots were enclosed with sheet steel. The dimensions of the plots were 40 × 100 cm (width × length). The slope gradient of each plot was approximately 15°. A hemicycle

**Table 1.** Plot Characteristics of the Study Sites

| Site | F1 | F2 |
|---|---|---|
| Elevation (m) | 1,261 | 1,286 |
| Vegetation coverage (%) | 20 | 50 |
| Dominant plant species | *Artemisia capillaris, Stipa bungeana, and Tripoli sater* | *Stipa bungeana, Tripoli sater, Artemisia giraldii, Setaria viridis, and Agropyron cristatum* |
| Biocrust coverage (%) | 90 | 85 |
| Moss coverage (%) | 20 | 75 |
| Biocrust thickness (mm) | 2.5 | 8.0 |
| Soil bulk density in 0–5 cm ($\mathrm{g \cdot cm^{-3}}$) | 1.13 | 1.20 |
| Biocrust cohesion ($\mathrm{kg \cdot cm^{-2}}$) | 0.07 | 0.44 |
| Biocrust O.M. content ($\mathrm{g \cdot kg^{-1}}$) | 7.64 | 13.73 |
| Soil O.M. in 0-5 cm ($\mathrm{g \cdot kg^{-1}}$) | 4.40 | 5.24 |
| Clay of soil in 0–5 cm (%) | 22.2 | 22.2 |
| Sand of soil in 0–5 cm (%) | 11.4 | 11.4 |

Note: O.M. = organic matter.

J. Hydrol. Eng., 2013, 18(4): 387-393

flume was set on the up-slope boundary of each plot to provide a constant volume of water flow. The water in the hemicycle flume was kept at a constant volume by using a Mariotte bucket. A small collection pool was positioned at the down-slope boundary of the plot to collect runoff and sediment.

### Plot Treatments

The following four treatments were designed for the experimental plots: (1) retaining biocrusts and plants intact (CP), (2) retaining biocrusts without plant canopies (plants canopies were cut off, CNP), (3) retaining plant canopies without biocrusts (biocrusts were scraped away, PNC), and (4) neither biocrusts nor plant canopies (plant canopies were cut off and biocrusts were scraped away, NCP). The simulated runoff flux was designed in accordance with the maximum potential runoff yield caused by a typical medium storm in the hilly Loess Plateau region (2 mm/min) on a standard plot (20 × 5 m). A maximum simulated runoff flow intensity of 16 L/min flux through a 40 cm wide outlet was set. Three levels (16.0, 12.0, and 7.8 L/min) of simulated runoff intensities were set in the study (Table 2). Scouring time was set at 15 min (which is the maximum time frequency for rainstorms in the research region). The 7.8 L/min simulated runoff experiments for CP and CNP treatments were cancelled because of no sediment yield being generated even after 30 min with a 16.0 L/min simulated runoff rate.

Runoff from the plot was collected every 3 min when there was any runoff yield at the outlet. The runoff was subsequently deposited and measured in the laboratory. Sediments were separated from runoff and weighed after they were weather dried.

**Table 2.** Experimental Design

| Scouring intensity (L/min) | Soil surface treatment | | | |
|---|---|---|---|---|
| | CP | CNP | PNC | NCP |
| Large (16.0) | y | y | y | y |
| Medium (12.0) | y | y | y | y |
| Small (7.8) | — | — | y | y |

Note: The letter y indicates that the treatment was conducted with the designed scouring intensity in the 13-year revegetated grassland. In 4-year revegetated grassland, only the medium scouring intensity was conducted at the four surface treatments. CP = retained biocrusts and plants intact; CNP = retained biocrusts without plant canopies; PNC = retained plant canopies without biocrusts; and NCP = retained neither biocrusts nor plant canopies (plant canopies were cut off and biocrusts were scraped away).

### Soil Antiscourability Index

In the study, an index, the soil erosion module ($K_w$), was introduced and used to express soil antiscourability with different treatments to eliminate the difference from runoff volume (Wu et al. 1993). In the study, $K_w$ ($g/m^2 \cdot mm$) is the quantity of sediment generated per unit soil area and runoff depth

$$K_w = \frac{W}{A \cdot H}$$

in which $K_w$ = soil erosion module ($g/m^2 \cdot mm$); $W$ = quantity of sediment yield (g); $A$ = area of plot ($m^2$); and $H$ = depth of runoff yield (mm).

In the study, a larger $K_w$ indicates a more substantial antiscourability.

## Results

### Runoff Yields with Different Treatments

Runoff rate and total runoff yield were markedly different with respect to the four soil surface treatments in the 13-year-old revegetated grasslands (Fig. 1, $P < 0.001$). Runoff yields in the first 15 min of scouring time in the plots of CP and CNP accounted for 76.1 and 87.4% of the total quantity of scouring water, respectively. In the plots for which the surface biocrusts had been scraped (PNC and NCP), runoff yields in the first 15 min were 61.0 and 69.4% of the total scouring water, respectively. In the experimental conditions, runoff was increased by 15.1% when retaining plant canopies, (CP-PNC) and by 16.0% when plant canopies were removed (CNP-NPC). Runoff yield was reduced by plant canopies. The percent ratio of runoff decreased by retaining plant canopies was 11.3 (with biocrusts) and 8.4 (without biocrusts), respectively, in the experimental conditions.

Runoff yields during the first 15 min of scouring from the 4-year-old revegetated grassland accounted for 87.4, 84.0, 82.4, and 80.2% of total scouring water under the treatments of CP, CNP, PNC, and NCP, respectively. No significant differences were found between the treatments in the 4-year-old revegetated grasslands.

Fig. 2 illustrates the maximum runoff rate that appeared at 6 min in the 13-year-old revegetated grassland, and after this point the rate of runoff yield became stable. Comparatively, in the 4-year-old revegetated grasslands, the maximum runoff rate was at 9 min after

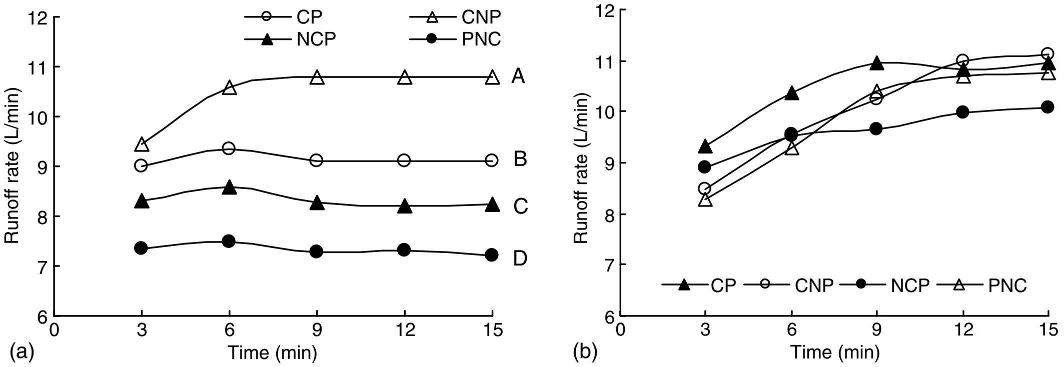

**Fig. 1.** Runoff yield rates with different soil surface treatments, i.e., biocrusts and plants (CP), biocrusts without plants (CNP), plants without biocrusts (PNC), and neither biocrusts nor plants (NCP), with a scouring intensity of 12.0 L/min in the two different aged revegetated grasslands: (a) 13 years of revegetation; (b) 4 years of revegetation; plotted runoff rates are the mean of every 3 min period during the experiment; the letters in (a) illustrate the significant difference ($P < 0.001$) in total runoff rates during the 15-min scouring period with the four treatments

J. Hydrol. Eng., 2013, 18(4): 387-393

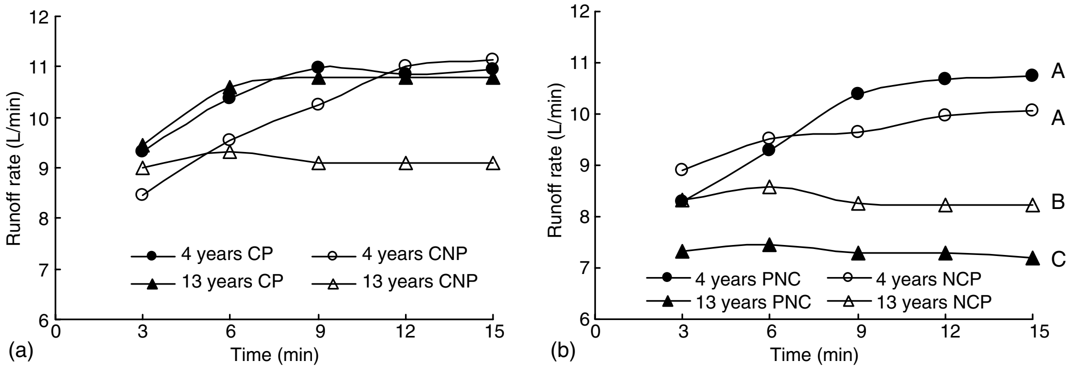

**Fig. 2.** Runoff rates with different successional stages of biological soil crust (BSC) and soil surface treatments with a scouring water intensity of 12.0 L/min in the two different revegetated grasslands: (a) with BSC; (b) without BSC; the runoff rates are mean of every 3 min during the experimental period; the letters in (b) illustrate the significant difference ($P < 0.001$) of the total runoff during the 15-min scouring period with the four treatments

the scouring began. The results suggest that the runoff process varied with the succession stages of biocrusts (Fig. 2). Runoff yields in the 13-year-old revegetated grasslands within the 15-min scouring period were reduced relative to that in the 4-year-old grasslands for the removal of the surface biocrusts, irrespective of whether plant canopies were retained.

### *Sediment Yield with Different Treatments*

There was no soil loss under the treatments of CP and CNP in the 13-year-old revegetated grasslands during the entire 15 min of scouring at 12 L/min simulated runoff intensity. No soil loss was recorded in such plots even when they were scoured at the same intensity (12 L/min) for longer than 60 min. Plots with biocrusts intact resisted on a scouring intensity of 16 L/min for a 20-min duration. However, in the plots under the treatments without biocrusts (PNC and NCP) in the 13-year-old revegetated grasslands, 839.8 and 924.0 g/m$^2$ of sediment intensities were recorded at the 12.0 L/min scouring intensity during the first 15 min; see Fig. 3(a). Sediments from PNC plots accounted for 90.8% of the NCP plots, indicating that plant canopies could reduce soil loss by approximately 10% in the authors' study. However, the effect of plant canopies on controlling soil loss was much reduced relative to that of biocrusts, which controlled soil loss completely in the experimental conditions.

As demonstrated in Fig. 3(b), soil loss process under the four treatments plots in the 4-year-old revegetated grasslands showed similar results as that in the 13-year-old revegetated grassland. In the 4-year-old revegetated grasslands, sediments intensity from plots of CP and CNP were 216.0 and 698.5 g/m$^2$ at the 12 L/min scouring intensity in the first 15 min. However, sediments intensity in plots of PNC and NCP increased to 4,796.5 and 8, 729.0 g/m$^2$ at the same scouring intensity, which was approximately 22 and 40 times higher, respectively, than that of CP. This indicates that, when compared with NCP, treatments CP, CNP, and PNC reduced soil loss by 97.5, 92.1, and 45.1% in the 4-year-old revegetated grasslands, respectively.

### *Effects of Biocrusts' Successional Stage on Sediment Yield*

Sediment yields were significantly influenced by biocrusts in the two successional stages (Fig. 3). Whereas very small soil losses were recorded in plots with early successional biocrusts, no soil loss was found in the plots with later successional biocrusts (Fig. 3). Early successional biocrusts were more susceptible to being degraded and scraped away by the scouring water, particularly when plant canopies were cut off.

There was a significant difference in the magnitude of sediment yields between the two revegetated grasslands when biocrusts were

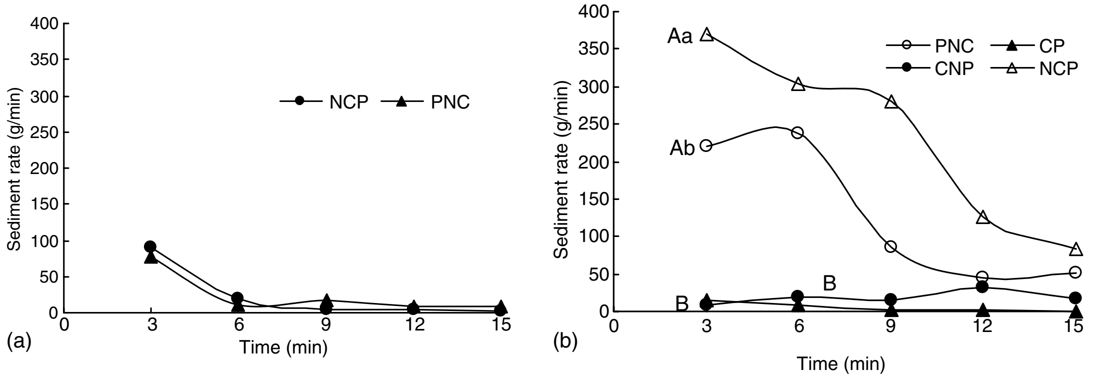

**Fig. 3.** Soil loss with under different soil surface treatments of CP, CNP, PNC, and NCP with the scouring water intensity of 12.0 L/min in the two different revegetated grasslands: (a) 13 years of revegetation; (b) 4 years of revegetation; the sediment loss rates are the mean of every 3 min during the experiment; the letters A, B, a, and b in (b) illustrate the significant difference ($P < 0.001$ for capital letters and $P < 0.05$ for lowercase letters) among the total sediment during the 15 min with the four treatments

J. Hydrol. Eng., 2013, 18(4): 387-393

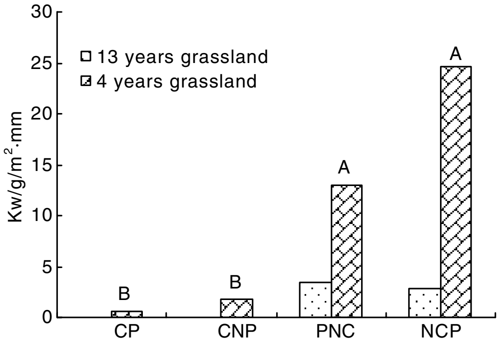

**Fig. 4.** Soil $K_w$ with different soil surface treatments with scouring water of 12.0 L/min in 15 min; the uppercase letters indicate significance at $P < 0.001$ levels for $K_w$ of different treatments in grassland revegetated for 4 years

scraped away. For PNC and NCP, sediments in the 4-year-old revegetated grasslands were five (with plants canopies) to nine (without plants canopies) times larger than that in the 13-year-old revegetated grasslands.

### *Soil Erosion Module ($K_w$) with Different Treatments*

The $K_w$ of both revegetated grasslands with the four treatments is shown in Fig. 4. In the experimental conditions, the $K_w$ of the 13-year-old revegetated grasslands containing biocrusts was zero irrespective of whether plant canopies were retained. However, when biocrusts were scraped from the soil surface, $K_w$ increased to $2.85\ \mathrm{g/m^2 \cdot mm}$ (without plant canopies) and $3.43\ \mathrm{g/m^2 \cdot mm}$ (with plant canopies), demonstrating the importance of biocrusts in this scenario.

The $K_w$ of the 4-year-old revegetated grasslands demonstrated a similar trend as described previously; however, the effect of plant canopies on soil antiscourability proved more significant. For the 4-year-old revegetated grasslands, $K_w$ was $0.5\ \mathrm{g/m^2 \cdot mm}$ in CP, and it increased to $1.8\ \mathrm{g/m^2 \cdot mm}$ when plant canopies were removed (CNP). The $K_w$ of PNC and NCP was 12.9 and $24.6\ \mathrm{g/m^2 \cdot mm}$, respectively, which was approximately 7 and 13 times greater, respectively, than that with CNP. This demonstrates the function of biocrusts on soil loss control. The $K_w$ of NCP doubled compared with PNC treatment, suggesting that vascular plant canopies had a positive effect on soil antiscourability on the revegetated grasslands with early successional biocrusts. However, the magnitude of the influence of plant canopies was quite limited compared with biocrusts.

### *Effect of Biocrusts' Successional Stages on Soil Erosion Module*

Fig. 4 illustrates the difference in $K_w$ between soils with different successional stages of biocrusts. Whereas biocrusts on the 4-year-old revegetated grasslands was gradually destroyed by scouring water, the subsequent successional stage of biocrusts in the 13-year-old revegetated grasslands remained intact. When biocrusts were removed, a difference in $K_w$ values of a factor of 4–8 between the two grasslands was evident, reflecting the effects of biocrusts and plant canopies on soil physical properties.

## Discussion

Following implementation of the Grain for Green program, biocrusts were presented extensively on soil surface of the revegetated grasslands in the hilly Loess Plateau region. This significantly altered soil surface chemical and physical properties, such as organic matter content, soil cohesion, porosity, and roughness (Zhao et al. 2006a, b). Changes in soil chemical and physical properties had a potential influence on runoff and soil to be lost (Belnap 2006; Eldridge and Greene 1994). The authors' research demonstrates that biocrusts exerted a significant effect on soil surface runoff. Soil surface runoff increased by 15–16% with respect to the presence of biocrusts in the revegetated grasslands, irrespective of whether vascular plant canopies were retained. Reviewed literature reports similar results, suggesting that biocrusts increased runoff by decreasing infiltration (Brotherson and Rushforth 1983; Kidron et al. 1999; Eldridge et al. 2000; Uchida et al. 2000; Kidron and Yair 1997; Kidron 2007), although there is less certainty on how the presence of biocrusts actually influences water infiltration and runoff relationships (Belnap 2006).

No significant difference was found in the total runoff volumes with different soil surface treatments on the 4-year-old revegetated grasslands, which suggests that biocrusts affected runoff differently in accordance with its successional stage (Belnap 2006). Biocrusts in their early successional stages had little influence on soil surface runoff compared with their subsequent presence.

Runoff rates in the 13-year-old revegetated grasslands stabilized more quickly compared with that in the 4-year-old revegetated grasslands. Influenced by cultivation before revegetation, soil surface morphology in grassland revegetated for 4 years was uneven and the runoff distribution was not uniform. This seemed to induce a runoff regime that fluctuated greatly in the grassland. Furthermore, beginnings of rill and gully erosion formed more easily and runoff increased quickly in the grassland revegetated for 4 years without biocrusts; see Fig. 3(b).

Given that the effect of biocrusts on infiltration and soil surface runoff was negative, it might be expected to increase surface erosion. However, influence of biocrusts on soil erosion control was quite significant (Belnap 2006; Uchida et al. 2000; Knapen et al. 2007). Analogously to a kind of skin on soil surface, biocrusts protected the soil from erosion effectively after 4 years of grassland recovery. Sediment reduction efficiency of early successional biocrusts and vascular plant canopies was 92 and 45%, respectively, in the grassland revegetated for 4 years. However, in their early successional stages (after 4 years of development), biocrusts significantly controlled soil loss. Furthermore, the presence (or lack thereof) of vascular plant canopies in the early revegetated grasslands had been more significant in controlling soil loss compared with that in the later revegetated grasslands. Biocrusts in the later successional stages demonstrated complete control of soil erosion on slopes of 15° in medium rainstorm conditions in the hilly Loess Plateau (2 mm/min). Sediment reduction of vascular plant canopies was only 10% in grasslands revegetated for 13 years when the later successional biocrusts were removed. The results demonstrate that the biocrusts' influence on soil erosion control was substantial and significantly related with its successional stages. Biocrusts played a more important role on soil erosion control in the hilly Loess Plateau slopelands relative to vascular plant canopies.

Soil surface structure can be improved by biocrusts. Soil porosity and aggregate stability of the subsequent successional biocrust stages were greater than that of the previous successional cyanobacteria crusts (Belnap et al. 2003). Furthermore, soil aggregate stability and porosity were a function of soil infiltration. In addition, the biocrusts themselves and the soil structure beneath the altered biocrusts may be the factors that cause the different runoff processes on the revegetated grasslands during different successional stages (Fig. 3).

Many previous studies have focused on the effects of vascular plants and litter on runoff and soil loss on the Loess Plateau

J. Hydrol. Eng., 2013, 18(4): 387-393

(Xu 2005; Zheng 2006; Zheng et al. 2007; Zhou and Shangguan 2005; Liu and Singh 2004; Zhou and Shangguan 2007). Several studies have indicated that improvements in soil antiscourability are primarily attributable to the restored vegetation on the hilly Loess Plateau (Zhou and Shangguan 2005, 2007; Ghidey and Alberts 1997; Zhang et al. 2004). Evidence from this study suggests that the effect of biocrusts on soil erosion was a function of the presence of vascular plants. Vascular plant canopies can affect the development and stability of biocrusts (especially during early successional stages) by shading, secretion, and stabilizing the soil surface (Eldridge 1993). The roots of vascular plants can also enhance the stability of soil, especially the soils beneath biocrusts (Zhou and Shangguan 2005), which was generally more important for soil antiscourability. Additionally, plant canopies play an important role in reducing surface splashing erosion because of physical interception and retardation during storms process (Woo et al. 1997; Gray and Leiser 1982). However, the authors' results show that, although plant canopies reduced soil loss by 10 and 45% on the 13- and 4-year revegetated grassland, respectively (Fig. 3), they had only a slight influence on soil antiscourability in comparison with biocrusts (Fig. 4), which reduced soil loss by more than 90% (Fig. 3).

Given the substantial role of biocrusts on the control of soil loss, further research is still necessary to demonstrate the mechanism of biocrusts stability, for quantifying the effects of biocrusts which with different components, thickness, and coverage on soil erosion. Furthermore, the formation of biocrusts could decrease soil loss and increase surface runoff from slopes to some extent. However, the influence of biocrusts on regional soil and water losses is still not clear. Further research on the previously noted questions would help establish regional soil and water loss prediction models, and help to provide guidance to local land managers.

Analysis at a larger scale suggested that soil loss on slopes could be significantly controlled after 4 years of revegetation because of the influence of early successional biocrusts and vascular plants. Soil loss from slopes could be completely controlled after 10 years of revegetation because of the presence of biocrusts in their later successional stages.

## Conclusions

Given the historical severity of soil erosion in the hilly Loess Plateau region of China, it is important to acquire a greater understanding of the influence of biocrusts on soil loss. Based on a series of water scouring experiments conducted in the two revegetated grasslands of different ages, the authors conclude that the formation and development of biocrusts following implementation of the Grain for Green project have significantly affected soil loss on slopes in the hilly Loess Plateau region. Biocrusts play a significant role in soil erosion control in the research area. Early successional biocrusts decreased soil loss by 92%, and biocrusts in the later successional stages completely controlled soil loss on slopes with rainfall events of 2 mm/min intensity.

Vascular plant canopies controlled 10% (in grassland revegetated for 13 years) and 45% (in grassland revegetated for 4 years) of soil loss in the experiments. However, biocrusts can control soil loss by 92% in grasslands revegetated for 4 years. Further, soil loss can be controlled completely by biocrusts in their later successional stage regardless of whether plant canopies are retained.

Biocrusts increased surface runoff yield in slopes to some extent and this was related with the particular successional stages of biocrusts. Surface runoff on slopes of 15° can be increased by 15–16% by the later successional biocrusts compared with the absence of biocrusts.

In the hilly Loess Plateau region, soil antiscourability was enhanced greatly by the biocrusts and the restored vegetation. On slopes of 15° with rain storms of a 2 mm/min intensity, $K_w$ was only 0.5 $\mathrm{g/m^2 \cdot mm}$ on grasslands revegetated for 4 years with early successional biocrusts and vascular plants. $K_w$ was zero on grasslands revegetated for 13 years with later successional biocrusts.

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J. Hydrol. Eng., 2013, 18(4): 387-393