Quantifying the surface covering, binding and bonding effects of biological soil crusts on soil detachment by overland flow

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ABSTRACT: Biological soil crusts (BSCs) have impacts on soil detachment process through surface covering, and binding and bonding (B&B) mechanisms, which might vary with successional stages of BSCs. This study was conducted to quantify the effects of surface covering, binding and bonding of BSCs on soil detachment capacity by overland flow in a 4 m long hydraulic flume with fixed bed. Two dominant BSC types, developed well in the Loess Plateau (the early successional cyanobacteria and the later successional moss), were tested using natural undisturbed soil samples collected from the abandoned farmlands. Two treatments of undisturbed crusts and one treatment of removing the above-ground tissue of BSCs were designed for each BSC type. For comparison, bare loess soil was used as the baseline. The collected soil samples were subjected to flow scouring under six different shear stresses, ranging from 6.7 to 21.2 Pa. The results showed that soil detachment capacity (D_c) and rill erodibility (K_r) decrease with BSC succession, and the presence of BSCs obviously increased the critical shear stress, especially for the later successional moss crust. For the early successional cyanobacteria crust, D_c was reduced by 69.2% compared to the bare loess soil, where 37.7% and 31.5% are attributed to the surface covering and B&B, respectively. For the later successional moss crust, D_c decreased by 89.8% compared to the bare loess soil, where 68.9% and 20.9% contributed to the surface covering and B&B, respectively. These results are helpful in understanding the influencing mechanism of BSCs on soil erosion and in developing the process-based erosion models for grassland and forestland. Copyright © 2017 John Wiley & Sons, Ltd.

KEYWORDS: biological soil crusts; binding and bonding effects; contribution rate; rill erodibility; loess plateau

Introduction

Soil detachment, defined as the dislodgement of soil particles from the soil matrix at a particular location on the soil surface by the erosive force of rainfall and/or overland flow, provides loose, non-cohesive sediment for the subsequent transport and deposition (Zhang *et al.*, 2003, 2009; Wang *et al.*, 2013). Soil detachment by overland flow, such as rill erosion, is a crucial process of sediment generation on hillslopes (Poesen *et al.*, 2003). It occurs when the scouring force of flowing water exceeds the threshold of soil resistance (Knapen *et al.*, 2007). Therefore, the erosive force of overland flow and the resistance of near soil surface characteristics are two factors influencing the soil detachment process (Wang *et al.*, 2014).

Overland flow is the external driving force for soil detachment (Zhang *et al.*, 2003; Wang *et al.*, 2014, 2015). For a given soil, hydraulics of overland flow (e.g. flow regime, discharge, depth, slope gradient, velocity, friction coefficient and sediment concentration) controls the process of detachment (Govers *et al.*, 1990; Zhang *et al.*, 2003). Soil detachment by

overland flow is also strongly influenced by the near soil surface characteristics (i.e. soil properties, surface roughness, plant litter, biological soil crust and plant root system) since it occurs at the interface of flowing water and soil (De Baets *et al.*, 2006, 2007; Knapen *et al.*, 2007; Rodríguez-Caballero *et al.*, 2012; Wang *et al.*, 2014), especially on grassland and forestland.

As an important component of near soil surface characteristics in arid and semi-arid regions, biological soil crusts (BSCs) are an assemblage of specialized organisms including cyanobacteria, algae, lichens and moss (Williams *et al.*, 1995; Belnap *et al.*, 2001). In general, BSCs develop from the early-successional cyanobacteria crust to the late-successional lichen and moss crusts (Ochoa-Hueso *et al.*, 2011). Although BSCs represent a small fraction of the soil profile, they profoundly influence many soil surface characteristics known to affect hydrological processes (Belnap, 2006; Chamizo *et al.*, 2012b; Rodríguez-Caballero *et al.*, 2015; Liu *et al.*, 2016). Previous studies reported that the presence of BSCs contributes cover and roughness to the soil surface, which absorb the energy of falling raindrops, modify soil surface interactions, and

reduce shear effect and the velocity of overland flow, thereby minimizing the detachment of soil particles (Belnap, 2006; Rodríguez-Caballero *et al.*, 2012). However, the effect of BSCs on the surface microtopography depends on the dominant types or successional stage of BSCs (Rodríguez-Caballero *et al.*, 2015). It is widely accepted that the later successional BSCs composed of lichens and mosses growing above the soil surface add greater roughness than the early successional cyanobacteria crust (Belnap, 2006; Rodríguez-Caballero *et al.*, 2015). Moreover, many studies have indicated that BSCs have the ability to enhance soil aggregates, resulting from the combination of physical binding effect (cyanobacteria filaments and moss rhizoids) and extruded bonding effect (polysaccharides and organic gels extruded by the cyanobacteria components) (Belnap, 2006; Chamizo *et al.*, 2012a), thus decreasing the overland flow and soil detachment rate (Liu *et al.*, 2016). Nevertheless, some other studies reported that BSCs reduced infiltration due to extrusion of hydrophobic compounds, which swell upon wetting, clogging soil pores, and enhancing runoff rate and soil detachment capacity by flowing water (Belnap, 2006; Wang *et al.*, 2014).

The changes in soil surface characteristics induced by BSC growth certainly affect the soil detachment process of overland flow (Belnap, 2006; Chamizo *et al.*, 2015). Knapen *et al.* (2007) investigated the effects of BSCs on soil detachment rate of concentrated flow in croplands and their results showed that BSCs significantly influenced soil detachment rate. The ability of the later succession moss crust was two times greater than the early succession algae crust in reducing soil detachment capacity. Wang *et al.* (2014) investigated the effects of near soil surface characteristics on soil detachment by overland flow on restored grassland. They found that BSCs contributed 14.9% to reduced soil detachment capacity of overland flow compared to the bare loess soil. Liu *et al.* (2016) quantified the effects of moss crust and mixed crust on the soil detachment process by overland flow on abandoned farmlands of the Loess Plateau and demonstrated that soil detachment capacity decreases exponentially with increase in BSC cover.

Generally, the roles of BSCs in promoting soil resistance to flowing water erosion can be attributed to the surface covering, and binding and bonding (B&B) effects (Belnap, 2006; Knapen *et al.*, 2007). The vertical structure of BSCs is characterized by a thin above-ground top crust and a sub-crust section with different physical and biological properties (Zhang *et al.*, 2006; Sylvie and Peter, 2012). The above-ground top crust (reflecting the surface covering effect) can increase soil surface roughness (Belnap, 2006; Rodríguez-Caballero *et al.*, 2012), thereby decreasing the velocity of flowing water and erosive force. Consequently, soil detachment capacity of overland flow declines (Wang *et al.*, 2014). The sub-crust (reflecting the B&B effects) constitutes cyanobacteria filaments and the anchoring structures of mosses and lichens. Analogous to plant root systems, they bind and connect soil particles together to enhance soil resistance to flow water erosion (Belnap *et al.*, 2001; Belnap, 2006; Chamizo *et al.*, 2009). Meanwhile, the cyanobacteria filaments can exude the extracellular polysaccharide materials to bond soil particles together though intermolecular bonding forces to increase soil aggregate stability (Knapen *et al.*, 2007; Mager and Thomas, 2011). As a result, the soil detachment capacity of overland flow also decreases.

The Loess Plateau is one of the most severely eroded regions in the world, due to heavy storms, sparse vegetation cover and intense human activities (Fu *et al.*, 2011). To control soil erosion, a long-term, policy-driven 'Grain for Green' project was implemented in 1999. More than 2 million hectares of low-yield steep farmlands (>15°) have been converted to forest lands or grasslands in the Loess Plateau to reduce soil erosion

and improve soil quality (Deng *et al.*, 2012). These changes in land uses lead to great variations in the near soil surface characteristics (Wang *et al.*, 2014), which provide suitable water and heat conditions for BSC development and growth. Several field investigations revealed that cyanobacteria crust and moss crust are widely distributed in the Loess Plateau. In mature vascular plant communities, BSCs (dominated by moss crust) often cover up to 60–70% of the soil surface, whereas BSC (dominated by cyanobacteria crust) cover can be up to 90% in the newly restored areas (Zhao *et al.*, 2010, 2014).

BSCs have great effects on the soil detachment process by overland flow through surface covering and B&B mechanisms, which likely vary with successional stages of BSCs. Some studies have been conducted to investigate and quantify the effects of BSCs on the soil detachment process of overland flow as a whole (Knapen *et al.*, 2007; Wang *et al.*, 2014). However, the relative contributions of BSC surface cover and B&B effects to the process of soil detachment by overland flow are still not clear. Therefore, the objectives of this study were: (1) to detect the effects of surface covering and B&B of BSCs on soil detachment by overland flow in chronological series of BSCs succession; and (2) to provide the correction coefficients of BSC factors (surface covering and B&B) of different BSC types for rill erodibility and critical shear stress.

Materials and Methods

Sampling sites

The experiment was conducted at the Ansai Station of Soil and Water Conservation of Chinese Academy of Sciences, which locates a typical loess hill and gully region of the Loess Plateau. The region's climate is semiarid continental, with an average temperature of 8.8°C and an annual precipitation of 505 mm, mostly in summer. Owing to poor management, most of the natural vegetation has been destroyed. Current principal land uses are grassland, woodland and wasteland. In this study, two abandoned hill slopes, located at Zhifanggou small watershed near the Ansai station, dominated by cyanobacteria crust (representing an early successional stage of BSC) and moss crust (representing a later successional stage of BSC) were selected for soil sampling (Table I). The roughness, intensity and type of pre-disturbance and vascular plant cover are fairly homogeneous for these sites. The physical properties and major plant species of different abandoned hill slopes are listed in Table II.

Treatments

Three treatments (expressed as T0, T1 and T2) were designed in this study to evaluate the potential effects of BSC cover and B&B of two typical BSCs on soil detachment by overland flow. The bare loess soil (The 3 cm layer of cyanobacteria crust and moss crust were removed, keeping just the undisturbed loess soil without BSC tissue) of T0. This used as the baseline because: (1) this can eliminate the influence of sub-crust tissue (confined to 0–2 cm) on soil detachment capacity; (2) BSCs significantly influence subsurface soil properties – in order to accurately quantify the effects of surface covering, B&B of BSCs on soil detachment capacity by overland flow, bare loess soil must avoid sharing similar properties to BSCs. For T1, the top crust was removed slightly using tweezers and a soft brush, and believed to have only B&B effects on soil mass. To ensure maximum elimination of interference to the sub-crust (cyanobacteria filaments and the anchoring structures of

Table I. Basic information of the sampling sites; all sites have a similar hillside landform and all soil types are loess

Dominant crust type	BSCs coverage (%)	Location	Elevation (m)	Vegetation characteristics	
				Coverage (%)	Primary vegetation
Cyanobacteria crust	82	36° 44' 35.7" N, 109° 18' 54.8" E	1247	35	<i>Artemisia capillaris</i> Thunb.
Moss crust	75	36° 45' 08.7" N, 109° 14' 52.6" E	1229	67	<i>Stipa bungeana</i> ; <i>Artemisia gmelinii</i>

Table II. Soil properties of sampling sites

Crust types	Cohesion	Particle size distribution			Organic matter	Water-stable aggregates
	(kPa)	Clay (%)	Silt (%)	Sand (%)	(g kg ⁻¹)	(0–1)
Cyanobacteria crust	10.56 ± 2.45 ^a	15.05	63.37	21.59	7.38 ± 0.34 ^a	0.45 ± 0.01 ^a
Bare1	8.71 ± 0.23 ^b	13.23	62.18	24.29	6.14 ± 0.19 ^b	0.40 ± 0.03 ^{ab}
Moss crust	12.75 ± 2.18 ^c	16.52	62.61	20.88	7.41 ± 0.26 ^a	0.67 ± 0.03 ^c
Bare2	9.23 ± 1.41 ^b	11.83	62.23	25.94	6.62 ± 0.32 ^b	0.53 ± 0.03 ^{bd}

Note: Values given represent average values ± standard deviation. The same letter means that differences are not significant at $p < 0.05$.

mosses), BSCs underwent atmospheric exposure before operations (crustal components above ground are brittle and easily removed, especially when they are dry). Compared with the baseline T0, T1 only had sub-crust effects, reflecting the B&B effects of BSCs on the process of soil detachment by overland flow. For T2, both top crust and sub-crust were included, representing the total effect of BSCs. The characteristics of BSCs under different treatments are listed in Table III.

Soil sampling and soil detachment capacity measurement

Intact soil samples were collected using steel rings (diameter 10 cm, height 5 cm) from the topsoil surface to measure soil detachment capacity by overland flow. Detailed sampling procedures can be found in previous studies (Zhang *et al.*, 2003). To quantify the effect of BSC surface cover and B&B on the soil detachment process of overland flow, each treatment was tested for five replicates under each flow shear stress (a total of six shear stresses). In total, for two BSC types and bare loess soil, 150 tests (2 crust types × 2 treatments × 6 shear stresses × 5 replications + bare loess soil × 6 shear stresses × 5 replications) were conducted. To ensure the same soil moisture, the collected soil samples were saturated for 8 h and then drained for 12 h for soil detachment capacity measurement.

Soil detachment capacity was measured in a 4.0 m long and 0.35 m wide flume (Figure 1). The test loess soil was glued on the flume bed surface to simulate the soil sample surface condition (Zhang *et al.*, 2003). Flow discharge was controlled by a series of valves and measured at the flume outlet with a plastic bucket and a volumetric cylinder. For a given combination of flow discharge and slope gradient, the maximum velocity at the water surface was measured using a fluorescent dye

method 12 times and modified by a reduction factor according to flow regime to obtain the average velocity (Luk and Merz, 1992). The average velocity was used to calculate the flow depth h (m):

$$h = \frac{Q}{Bv} \quad (1)$$

where Q is the flow discharge (m³ s⁻¹), B is the flume width (m) and v is the mean flow velocity (m s⁻¹). The calculated average flow depth varied from 0.0030 to 0.0056 m in this study. The flow shear stress (τ , Pa) was calculated as follows:

$$\tau = \rho_w g h S \quad (2)$$

where ρ_w is the density of water (kg m⁻³), g is the constant of gravity (m s⁻²) and S is the slope gradient (m m⁻¹). Six combinations of flow discharge (0.0043–0.01 m² s⁻¹) and flume bed gradient (17.4–42.3%) were utilized in this study, resulting in six different shear stresses of 6.65, 9.45, 12.46, 15.12, 17.98 and 21.21 Pa, respectively (Table IV).

The flume bed gradient and flow discharge were adjusted to the desired values. The soil sample was set into a hole on the flume bed (0.5 m from the flume outlet) and was scoured under the desired flow shear stress and ended until a certain scouring depth was reached to standardize the influence of the ring rim (Nearing *et al.*, 1991; Zhang *et al.*, 2003). The scouring time varied from 15 to 600 s. Soil detachment capacity was calculated as follows:

$$D_c = \frac{W_b - W_e}{t \times A} \quad (3)$$

where W_b is the dry weight of soil sample before detachment test (kg), W_e is the dry weight of soil sample after detachment

Table III. The BSCs treatment participated in the process of soil detachment by overland flow

Treatment name	Surface of subsurface factors	Treatment effects
T0	Undisturbed loess soil	Baseline condition
T1	Undisturbed sub-crust	Effects of BSC's below-ground tissue, including chemical bonding and physical binding
T2	Undisturbed biological soil crust	Total BSCs effects

Figure 1. Soil sampling and experimental setup: (a) bare soil; (b) cyanobacteria crust; (c) moss crust; (d) schematic diagram of the flume experimental setup. [Colour figure can be viewed at wileyonlinelibrary.com]

Table IV. Hydraulic parameters used in this study

Flow discharge ($\text{m}^2 \text{s}^{-1}$)	Slop gradient (%)	Mean flow velocity (m s^{-1})	Water depth (mm)	Shear stress (Pa)
0.0043	17.4	1.11	3.9	6.65
0.0071	17.4	1.30	5.6	9.45
0.0043	42.3	1.44	3.0	12.46
0.0057	42.3	1.58	3.7	15.12
0.0100	34.2	1.88	5.4	17.98
0.0100	42.3	1.96	5.1	21.21

test (kg), t is the test period (s) and A is the section area of the soil sample (m^2). For each treatment, five samples were tested under each shear stress and the mean was deemed as the detachment capacity for that shear stress, crust treatment and crust type. The mean soil detachment capacity of six different shear stresses was used to analysis the contribution rates for each crust treatment and crust type.

$\text{RDC}_{\text{Total-BSCs}}$ is the reduction of soil detachment capacity under undisturbed BSCs ($\text{kg m}^{-2} \text{s}^{-1}$). D_{C-T0} , D_{C-T1} and D_{C-T2} are the soil detachment capacity of T0, T1 and T2 ($\text{kg m}^{-2} \text{s}^{-1}$), respectively:

$$\text{CR}_i = \frac{E_i}{\sum E_i} \times E_{\text{Total-BSCs}} \quad (7)$$

Reduction of detachment capacity and contribution rate

The reductions of soil detachment capacity (RDC) caused by BSCs including sub-crust (B&B effects) and top crust (cover effect) were calculated using Equations (4) and (5), and the total BSCs was calculated using Equation (6). The contribution rate (CR) to soil detachment was computed using Equation (7):

$$\text{RDC}_{\text{BSC-B\&B}} = D_{C-T0} - D_{C-T1} \quad (4)$$

$$\text{RDC}_{\text{BSC-cover}} = D_{C-T1} - D_{C-T2} \quad (5)$$

$$\text{RDC}_{\text{Total-BSCs}} = D_{C-T0} - D_{C-T2} \quad (6)$$

where $\text{RDC}_{\text{BSC-B\&B}}$ is the reduction of soil detachment capacity by the sub-crust ($\text{kg m}^{-2} \text{s}^{-1}$), $\text{RDC}_{\text{BSC-cover}}$ is the reduction of soil detachment capacity by top crust ($\text{kg m}^{-2} \text{s}^{-1}$) and

where CR_i is the contribution rate of each factor i (BSC surface covering, BSCs–B&B, respectively) in reducing soil detachment capacity (%). $E_{\text{Total-BSCs}}$ is the effect of intact BSCs on reducing soil detachment (%; Equation (8)) and E_i is the effect of factor i on reducing soil detachment (%; Equations (9) and (10)):

$$E_{\text{Total-BSCs}} = \frac{\text{RDC}_{\text{Total-BSCs}}}{D_{C-T0}} \times 100\% \quad (8)$$

$$E_{\text{BSCs-B\&B}} = \frac{\text{RDC}_{\text{BSCs-B\&B}}}{D_{C-T0}} \times 100\% \quad (9)$$

$$E_{\text{BSCs-cover}} = \frac{\text{RDC}_{\text{BSCs-cover}}}{D_{C-T1}} \times 100\% \quad (10)$$

Note that $\text{CR}_{\text{BSCs-B\&B}} + \text{CR}_{\text{BSCs-cover}} = \text{CR}_{\text{Total-BSCs}}$.

Rill erodibility and critical shear stress

Rill erodibility (K_r , s m^{-1}) and critical shear stress (τ_c , Pa) were estimated for each treatment as the slope and intercept on the x-axis of the regression linear line between flow shear stress (τ) and soil detachment capacity (D_c) as described in the WEPP (Water Erosion Prediction Project) model (Nearing *et al.*, 1989), as follows:

$$D_c = K_r(\tau - \tau_c) \quad (11)$$

where K_r is the rill erodibility (s m^{-1}), τ is the flow shear stress (Pa) and τ_c is the critical shear stress (Pa).

Statistical analysis

The differences in D_c between BSCs were detected by a method of multiple comparisons, which was also used for both RDC and CR. The relationship between D_c and shear stress was fitted by a linear regression method, and the goodness of fit results were evaluated by the coefficient of determination. All statistical analyses and graphical displays were made using R 3.3.0 software for Windows (R Development Core Team, 2016).

Results

Contributions of surface covering and B&B on soil detachment

The treatment of biological soil crust significantly influenced soil detachment capacity by overland flow. As seen in Figure 2, the bare loess soil (T0) shows higher soil detachment capacity than other treatments. For the cyanobacteria crust, the mean soil detachment capacity of sub-crust (T1) and undisturbed crust (T2) are 40.4% and 69.2% less than those of

bare loess soil ($2.997 \text{ kg m}^{-2} \text{ s}^{-1}$, T0), respectively. The effects of the sub-crust (T1) and undisturbed crust (T2) of BSCs on soil detachment capacity of overland flow are obviously different between the cyanobacteria crust and moss crust (Figure 2). For the later successional moss crust, the mean soil detachment capacity of sub-crust (T1) and undisturbed crusts (T2) are 26.2% and 89.8% less than those of bare loess soil ($0.593 \text{ kg m}^{-2} \text{ s}^{-1}$, T0), respectively (Figure 2).

RDC caused by top crust, sub-crust and undisturbed crust are quite different (Table V). The mean RDC values under different treatments range from 0.865 to $2.075 \text{ kg m}^{-2} \text{ s}^{-1}$ for cyanobacteria crust, and varied from 0.155 to $0.534 \text{ kg m}^{-2} \text{ s}^{-1}$ for moss crust. These results indicated that BSCs could effectively enhance soil resistance to flowing water erosion through their surface covering and B&B effects. As a surface phenomenon, BSCs shielded the soil surface and protected underlying soils from detachment by flowing water. Meanwhile, BSCs increased soil surface roughness and reduced flow velocity, thereby reducing the scouring of flowing water (effects of surface cover, which was represented by the treatment of top crust in this study). Below the soil surface, cyanobacteria filaments and moss rhizines bind soil particles together and form a matrix strongly influencing soil stability; cyanobacteria could increase soil aggregate stability by bonding soil particles with polysaccharide exudates (B&B, represented by the treatment of sub-crust in this study).

As mentioned above, the top crust (surface covering) and the sub-crust (B&B) have key roles in reducing soil detachment capacity of overland flow. However, the contributions of the top crust and the sub-crust to the soil detachment process of overland flow remain unknown. Hence the contribution rates of top crust, sub-crust and undisturbed crust are calculated using Equation (7) and shown in Figure 3. For cyanobacteria crust, soil detachment capacity reduced by 69.2% compared to that of bare loess soil, where 37.7% and 31.5% are caused by top crust (surface covering) and sub-crust (B&B). For moss crust, soil detachment capacity decreased by 89.8% compared to those of bare loess soil, where 68.9% and 20.9% are deduced by the top crust (surface covering) and sub-crust (B&B). The contribution of the BSCs increased with BSC succession because later successional moss crust has more biomass above the soil surface. For example, the contribution of top crust (covering effect) of later successional moss crust was 1.8 times greater than that of the early successional cyanobacteria crust.

Soil resistance to flowing water erosion with biological soil crusts succession

Following Nearing *et al.* (1989), the soil resistance to flowing water erosion (rill erodibility K_r and critical shear stress τ_c) is estimated using the measured soil detachment capacity and flow shear stress. The fitted K_r and τ_c of different treatments

Table V. Reduction in soil detachment capacity with different BSC characteristics relative to bare loess soil

Factor	Reduction of soil detachment capacity ($\text{kg m}^{-2} \text{ s}^{-1}$)	
	Cyanobacteria crust	Moss crust
BSC _{cover}	0.865	0.377
BSC _{B&B}	1.210	2.559
Total BSC	2.075	2.36

Figure 2. Variation of the soil detachment capacity for each treatment. T0 is the bare loess soil, T1 is the sub-crust (B&B effects) and T2 is the total BSCs effect. The same letter means that differences are not significant at $p < 0.05$.

Figure 3. Contribution rates of different BSCs factors. Total BSCs are the undisturbed crusts; sub-crust is binding and bonding effect of BSCs; top-crust is the cover effect of BSCs.

for two BSCs are calculated using Equation (11) and are shown in Figure 4. For the cyanobacteria crust, K_r under T1 treatment (sub-crust) was reduced by 23.9% compared to that of bare loess soil (T0, 0.3404 s m^{-1}). When the cover effect of BSC is considered (T2, total cyanobacteria crust), K_r is reduced by 41.6% compared to T1 treatment (sub-crust). For the moss crust, K_r under T1 treatment (sub-crust) is reduced by 52.9% compared to the bare loess soil (T0, 0.1659 s m^{-1}). Taking into consideration the surface covering effect, K_r is reduced by 87.8% relative to that under T1 treatment (sub-crust). The critical shear stresses (τ_c) of cyanobacteria crust changed from 5.61 to 7.71 Pa and ranged from 6.47 to 8.04 Pa for moss crust (Figure 4). Compared to bare loess soil (T0), the critical shear stress of T1 treatment (sub-crust) and T2 treatment (total BSC) increased by 23.1% and 37.4% for cyanobacteria crust. Regarding the later successional moss crust, the critical shear stress of T1 treatment (sub-crust) and T2 treatment (total BSC) increased by 16.2% and 24.3% compared to that of the bare loess soil.

Discussion

Contributions of surface covering and B&B on soil detachment

BSCs have a substantial impact on the process of soil detachment. Our results showed that the mean soil detachment capacity of bare loess soil is 3.2 times greater than that of cyanobacteria crust (T2), and the mean soil detachment capacity of base soil is 9.8 times higher than that of moss crust (T2). It is obvious that the later successional moss crust is more effective in reducing soil detachment capacity by overland flow than the early successional cyanobacteria crust. These results are consistent with the finding of Knapen *et al.* (2007), who investigated the effects of BSCs on soil detachment capacity of overland flow in croplands and showed that soil detachment capacity decreases with crust development. Eldridge and Greene (1994) also found, under simulated rainfall on a semi-arid soil in Australia, that the splash erosion rate declined exponentially with increasing BSC coverage. In fact, it is widely accepted that the BSCs shield the soil surface from both wind and water erosion (Belnap, 2006; Knapen *et al.*, 2007; Chamizo *et al.*, 2015; Liu *et al.*, 2016). However, some other studies reported that BSCs limited infiltration due to extrusion of hydrophobic compounds and clogging of soil pores when wetting, thus increasing the amount and velocity of water runoff, which determine the process governing overland flow generation (Belnap, 2006; Fischer *et al.*, 2010; Chamizo *et al.*, 2012a, 2012b; Rodríguez-Caballero *et al.*, 2013). To examine the effects of BSCs on runoff and erosion, Zhao *et al.* (2013) found that, under different scouring water fluxes, the presence of BSCs plays a critical role in preventing soil erosion by water in semiarid regions, although there was potential increase in runoff. Liu *et al.* (2016) also reported that BSCs have a significant effect on soil detachment by overland flow, which could be estimated using flow shear stress and BSC coverage. Moreover, the erosion rate of BSC-covered surfaces is lower than the physical crust (Chamizo *et al.*, 2009; Rodríguez-Caballero *et al.*, 2013). Eldridge and Kinnell (1997) found that water erosion of BSC-covered soil is five times less compared to the physical crust (such as raindrop impact or depositional), mainly because both the external morphology and the internal structure of the physical crusts are quite different from BSCs (Belnap, 2006). In contrast, the presence of physical crust seals and smoothens surfaces, reduces infiltration and increases the velocity of overland flow (Chamizo *et al.*, 2015). Using scanning

Figure 4. Soil detachment capacity (D_c) as a function of shear stress (τ) as an example to estimate rill erodibility and critical shear stress: (a) cyanobacteria crust; (b) moss crust.

electron microscopy, previous studies presented a detailed analysis of the internal structure of BSCs and physical crusts (Belnap, 2006; Zhang *et al.*, 2006; Williams, 2012). In general, the role of BSCs in enhancing soil resistance to flowing water erosion is attributed to the surface cover (modifying the surface micro-topography, such as soil roughness), and B&B effects (change soil structure). However, in previous studies, BSCs were regarded as a whole system in discussions of their effects on soil detachment process by overland flow (e.g. Knapen *et al.*, 2007; Wang *et al.*, 2013). Quantifying the effects of surface covering and B&B of BSCs in reducing soil detachment capacity in this paper is helpful for understanding the soil erosion mechanism of soils covered by BSCs.

In this study, we found that the contributions of top crust (surface covering) increase with the stage of BSC development (cyanobacteria to moss) from 37.7% to 68.9% (Figure 3). For the cyanobacteria crust, the top crust is about 0–2 mm thick and is composed of small packed particles and most of the organic material (Hagai *et al.*, 2015). Therefore, high-intensity precipitation and flow scouring can break apart the top crust of cyanobacteria, causing the detachment of subsoil. Unlike cyanobacteria crust, moss crust has most of its biomass above the soil surface, which is more effective in protecting the underlying soils from scouring by the overland flow (Belnap, 2006). Moreover, the top organisms of BSCs can absorb large amounts of water, increasing their volume several times over their dry volume (Belnap, 2006), which may affect the surface microtopography, and thus impact infiltration and soil erosion (Rodríguez-Caballero *et al.*, 2015). However, water absorption capacity depends on the type of BSCs and the successional stage. More development moss crust can expand their cover and biomass by up to 13 times when wetted, whereas the early successional cyanobacteria crust absorb up to eight times their dry weight (Belnap, 2006; Rodríguez-Caballero *et al.*, 2015). Thus later successional moss crust confers greater roughness to soils than early successional cyanobacteria crust when wetted, and these structural differences in the top crust made the later successional moss crust more effective at stabilizing surfaces than the cyanobacteria crust.

Variation in the contribution of sub-crust was inversely related to the top crust; the contribution of sub-crust (B&B effects) decreased with the stage of BSC development (cyanobacteria to moss) from 31.5% to 20.9% (Figure 3). As a pioneer crust, cyanobacteria are the first colonizers (Belnap, 2006; Chamizo *et al.*, 2015); the sub-crust (B&B effects) of cyanobacteria filaments can bind soil particles and contribute amounts of organic carbon via carbon fixation, which provides these soils with a tremendous resistance to movement of water (Belnap, 2006). We also found that the effect of cyanobacteria crust on organic matter and soil cohesion is, especially, significantly higher than bare loess soil (Table II), which greatly enhanced the effects of the top layer of soil in reducing soil detachment by overland flow. The contributions of sub-crust (B&B effects) of cyanobacteria are significant and accounted for nearly half of the effects of the total cyanobacteria crust. The sub-crust (B&B effects) of moss also plays an important role in protecting the soil from erosion through anchoring structures binding soil particles to increase soil aggregate stability and soil cohesion (Table II). However, for the later successional moss crust, the mean soil detachment capacity of bare loess soil was reduced by 80.2% compared to that of cyanobacteria crust, which can be attributed to the differences in soil properties, such as cohesion, organic matter content and water-stable aggregate, as shown in Table II. Therefore, the contribution of sub-crust of moss is lower than that of cyanobacteria crust in improving the resistance of the soil to flowing water.

As discussed above, BSCs significantly affect soil detachment capacity by overland flow through modifying the surface microtopography and enhancing soil aggregates, and the different developmental stages of BSCs have different effects on the hydrological and erosive response of soils covered by BSCs at patch scale (Rodríguez-Caballero *et al.*, 2012). When the later successional-stage BSCs cover the spaces between vascular plants, it is likely that infiltration would increase and erosion would decrease. Moreover, at hillslope scale, BSCs would roughen the soil surfaces, causing slower overland flow, allowing more time for infiltration and decreasing the scouring force of flowing water. More generally, we expect BSCs to influence the hydrological and geomorphological processes at a much larger scale (e.g. landscape scale).

Soil resistance to flowing water erosion with biological soil crusts succession

Rill erodibility (K_r) and critical shear stress (τ_c) are two important parameters reflecting the effects of soil resistance to erosive forces (Nearing *et al.*, 1989). For the early successional cyanobacteria crust, rill erodibility (K_r) of bare loess soil (T0) was 1.3 and 2.2 times greater than those of the T1 treatment (sub-crust) and T2 treatment (total crust), while, for the later successional moss crust, rill erodibility (K_r) of base soil (T0) was 2.1 and 17.5 times greater than those of the T1 treatment (sub-crust) and T2 treatment (total crust). These results imply that the effects of both top crust (covering effect) and sub-crust (B&B) of BSCs can increase the resistance of the soil to scouring by the overland flow. Other authors (e.g. Belnap, 2006; Liu *et al.*, 2016) pointed out that the BSCs not only create a coherent living crust that covers the soil surface, but also that, underneath the top crust, filaments and residual organic matter also bind with the soil particles, strongly enhancing soil stability. In this study, we found that the top crust (surface covering) has a larger effect than the sub-crust (B&B) on increasing the soil resistance to erosion by flowing water, especially for the later successional moss crust. This is likely due to the surface covering effect of BSCs, which reduces the contact area of flow water with the soil particles, thus weakening the shear force to separate soil particles. This agrees with Liu *et al.* (2016), who studied the influence of BSC coverage on soil detachment by overland flow, and who pointed out that rill erodibility of bare soil is significantly greater than those of BSCs; covered soil and rill erodibility decrease with coverage of BSCs. Furthermore, the later successional moss crust coverage is more effective in reducing soil erosion rate than the early successional crust (Knapen *et al.*, 2007). Eldridge and Greene (1994) also reported an exponential decline in sediment removal by splash with increasing BSC cover in a semiarid context. Although a different erosion process was studied, it is plausible that the later successional moss crust is more effective in reducing soil erosion rates than the early successional crust.

Soil detachment in rills occurs when flow shear stress exceeds the critical shear stress of the soil (Wang *et al.*, 2013). Our results demonstrated that the presence of such crusts on the soil surface increases the flow shear stress needed to overcome the impacts of BSCs on soil stability. As seen in Figure 4, the critical shear stress (τ_c) of sub-crust (T1) and total crust (T2) were 1.2 and 1.4 times higher than those of bare loess soil (T0, 5.61 Pa) for the cyanobacteria crust, while, for the later successional moss crust, critical shear stress (τ_c) of sub-crust (T1) and total crust (T2) were 1.1 and 1.2 times greater than those of bare soil (T0, 6.47 Pa). This is supported by the rill erodibility found, which showed that both top crust (covering

effect) and sub-crust (B&B) of BSCs play a critical role in soil stabilization. Knapen *et al.* (2007) studied the influence of BSCs on the soil detachment by overland flow in croplands, and pointed out that the later successional moss crust was more effective in increasing critical shear stress than the early successional algae crust and bare soil. Moreover, in their flume experiments on the Loess Plateau of China, Wang *et al.* (2013) found that the critical shear stress increased with increasing thickness of BSCs. However, no differences were found between different BSC cover classes for moss crust (Liu *et al.*, 2016), which was probably caused by the choice of sampling. In a previous study (Liu *et al.*, 2016), we found that BSCs with different coverages were selected for soil sampling, which means that the samples are a complex mosaic of BSCs and bare soil. This may result in samples' uneven loading when flow scouring, thus affecting the critical shear stress of soil-covered BSCs.

Conclusions

After calculating the contribution of different types of BSC factors (top crust and sub-crust) on soil detachment capacity by overland flow, we found that BSCs have great effects on the soil detachment process through surface covering and B&B mechanisms. However, the effect of BSCs on soil detachment capacity depends on the type or developmental stage of the BSCs. For the early successional cyanobacteria crust, soil detachment capacity reduces by 69.2% compared to the bare loess soil, of which 37.7% and 31.5% are attributed to surface cover and B&B; for the later successional moss crust, soil detachment capacity decreases by 89.8% compared to the bare loess soil, of which 68.9% and 20.9% are attributed to surface covering and B&B. Moreover, we also found that both soil detachment capacity and rill erodibility decrease with BSC succession. Meanwhile, the presence of BSCs obviously increases the critical shear stress, especially for the later successional moss crust. Generally, the accumulated effects of top crust (covering effect) and sub-crust (B&B) of BSCs enhance the ability of the soil to resist detaching by overland flow, and the effect of top crust (covering effect) plays an increasingly important role in reducing soil detachment as the BSCs succession. The findings of this study are helpful in understanding the influencing mechanism of BSCs on soil erosion and in developing process-based erosion models for grassland and forestland.

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