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ORIGINAL PAPER

Response of biological soil crusts to raindrop erosivity and underlying influences in the hilly Loess Plateau region, China

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Abstract Biological soil crusts (biocrusts) are ubiquitous living covers in arid and semiarid regions, playing a critical role in soil erosion control in semiarid regions. So far, research separating the multiple mechanisms of erosion control by biocrusts has been limited. It was problematic to link the influence of biocrusts to existing erosion models. In the present study, the response of biocrusts of different successional stages to raindrop erosivity and underlying influences was investigated. Using single drop simulated rainfall, the erosion controlling capacities of biocrusts were analyzed from an energetic perspective. The results showed that biocrusts caused a dramatic improvement of soil erosion resistance, which depended on species composition and increased considerably with higher succession stages. While the accumulated raindrop kinetic energy sustained by dark cyanobacterial crusts was 0.93 J ($\sim$15 times higher than that of bare soil), that of 60 % moss covered crusts reached values up to 20.18 J ($\sim$342 times higher than that of bare soil) and for 80 % moss covered crusts even 24.59 J were measured. Besides the composition and successional stages, the resistance of biocrusts to raindrop erosivity was related to the substrate soil moisture, soil texture, slope gradients and seasonal variation. The accumulated raindrop kinetic energy measured for cyanobacterial crusts was highest

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on silty, followed by loamy and sandy soil. For moss-dominated crusts raindrop kinetic energy was highest on sandy, followed by silty and loamy soil. Dry biocrust samples reached significantly higher accumulated raindrop kinetic energies compared to moist biocrusts, whereas the moisture content within moist crusts did not have a significant influence. Erosion resistance increased significantly with higher slope gradients. The resistance capacities of biocrusts during monsoon and post-monsoon were significantly higher than these of pre-monsoon biocrusts. Our results suggest that the influence of biocrusts can be included into erosion models from an energy point of view. The raindrop kinetic energy resistance capacity provides a potential bridge between biocrust succession and soil erodibility in commonly used erosion models.

Keywords Raindrop splash · Water erosion · Cyanobacterial crusts · Moss crusts · Successional stage

Introduction

Biological soil crusts (Biocrusts) consist of a complex community of cyanobacteria, algae, lichens, mosses, fungi, and other bacteria that live within the uppermost millimeters of the soil (Belnap et al. 2003). They are well known for their ability to stabilize soil surfaces and consequently reduce soil loss from wind and water erosive forces (Warren 2003; Eldridge and Greene 1994a, b). Meanwhile, numerous studies have been conducted worldwide on the influence of biocrusts on soil erosion. Almost without exception, results of the studies indicate that soil erosion is dramatically reduced due to the presence of biocrusts (Eldridge and Greene 1994b; Belnap and Gillette 1997; Warren 2003; Gaskin and Gardner 2001). For instance, Belnap and Gillette (1997) found the threshold friction velocity (TFV, the wind speed at which soil particles are detached and transportable) of a sandy soil on the Colorado Plateau in the USA to be extremely low (16 cm s^{-1}) compared to that of fully developed biocrusts (376 cm s^{-1}) within the same area. On the other hand, the TFV of biocrusts is known to be easily reduced by disturbance (Belnap and Gillette 1997; Leys and Eldridge 1998). Belnap and Gillette (1997) observed that TFVs of biocrusts, which had been relatively undisturbed for over 20 years, were four and seven fold higher compared to biocrusts which had been disturbed 5 or 1 year before. Similarly, Leys and Eldridge (1998) found that TFVs could be reduced by 57 % even by a moderate disturbance in a loamy soil in southeastern Australia.

For water erosion, already in the 1940s some researchers had shown that biocrusts could improve soil resistance against the detachment and overland flow of runoff (Booth 1941; McCalla 1946; Fletcher and Martin 1948). Somewhat later, Faust (1970, 1971) found soil loss to be markedly decreased when the bare soil surface was inoculated with naturally occurring cyanobacteria. Eldridge and Greene (1994b) observed that biocrusts of the semi-arid woodlands in Eastern Australia had a stabilizing effect against water and wind erosion, being positively related to soil crust coverage. Recently, a study conducted in the hilly Loess Plateau region of China showed that a four-year rehabilitated vascular plant community (grass and herbaceous) with biocrusts in-between reduced sediment transport by 97.5 %. When the plants were removed, the crusts caused the sediment transport to still be reduced by 92.1 %, whereas the plant canopy alone reduced sediment transport by only 45.1 %. The moss dominated crusts, which had developed by the thirteenth year, controlled soil erosion completely, even during runoff events generated by rainstorms peaking in rain intensities of more than 90 mm/h (Zhao and Xu 2013).

Soil erosion imposes many problems on arid and semiarid regions like the hilly Loess Plateau region of China (Shi and Shao 2000). The prominent monsoon, the hilly and gully topography, plus the excessive cultivation on slopes make soil erosion by raindrops and runoff flow inevitable. Additionally, soil in the region with its deep, loose loess characteristics (a loamy aeolian deposit) is extremely erodible, fragile and degraded (Xu et al. 2006a, b; Shi and Shao 2000). Therefore, soil erosion presents a severe ecological problem. It has been estimated that soil erosion exceeded 10,000 Mg km^{-2} $year^{-1}$ in the region before 1999 (Liu 1999; Shi and Shao 2000). Being aware of the harmful consequences of erosion, such as sediment loads in the hydrographic net and degradation of soil quality, an ecological restoration project named "Grain for Green" was implemented in the Hilly Loess Plateau region (Uchida et al. 2005). One major activity of the project is to retransform the crop lands on steep slopes ($\geq$25°) into grasslands and shrublands in order to restore ecosystem functions of the vegetation (Uchida et al. 2005; Deng et al. 2012). Biocrusts are widespread in the open spaces between vascular plants in the rehabilitated lands (Zhao et al. 2006; Wang et al. 2010) and field investigations revealed average coverage values up to 60–70 % in mature vascular plant communities. In newly restored areas, biocrusts mostly dominated by cyanobacteria already appear within the first year of restoration and could cover up to 90 % of the surface area in the following years. A rapid re-establishment of cyanobacteria after disturbance was also observed by Dojani et al. (2011) on biocrusts in southern Africa, who measured the same coverage values of crusts already 8 months after disturbance. Such high biocrust coverage effectively protects soil against water erosion in conjunction with the gradually rehabilitating vascular plants (Zhao et al. 2006; Zheng et al. 2007; Zhao and Xu 2013).

Whereas biocrusts have been widely shown to have a substantial influence on erosion, their impact still needs to be adequately accounted for in erosion models. There are quite a number of different erosion prediction models in use with the revised universal soil loss equation (RUSLE) and its predecessor USLE as well as the water erosion prediction project erosion model (WEPP) probably being the most widely used ones.

Soil erosion is the process of detaching and transporting individual soil particles or small aggregates. The process could be influenced by plants, including nonvascular plants, as well as soil properties (Morgan 2005). The effect of biocrusts, which are mainly composed of nonvascular plants, on soil erosion may influence two erosion factors. On the one hand they may influence soil erodibility (K factor) by improving soil properties, such as accumulating finer particles (Belnap et al. 2003; Chamizo et al. 2012). On the other hand, biocrusts increase soil organic matter content and enhance the amount and stability of aggregates by polysaccharide exudates as well as by physical enmeshment of soil particles, thus affecting the cover-management factor (C factor). Hence, to link the influence of biocrusts to the erosion models, we may, at least in theory, add their impact to the erodibility (K factor) or the cover-management factor (C factor) or both. To meet this objective, it is necessary to determine the relationship between biocrust developmental stages and their influence on the K factor as well as the C factor.

So far, although numerous studies have been conducted on the influence of biocrusts on soil erosion, only a few had been designed to discriminate between the effect of biocrusts on soil erodibility (the K factor) and on protection (the C factor; Bowker et al. 2008; Gao et al. 2013). Based on extensive field surveys and measurements, Bowker et al. (2008) found that the C factor in RUSLE was considerably more influenced by biocrusts than the K factor. However, more recent research carried out in the Hilly Loess Plateau region revealed, that in addition to improving the stability of soil aggregates, the structure of the surface soil was altered by the formation of biocrusts. The soil within biocrusts formed a uniquely layered structure with a much stronger stability in the horizontal than in the vertical direction. For late-successional moss-dominated crusts, only 4.8 % of the crust area was lost after shaking 930 rounds in water, whereas the thickness loss of the same crusts was 57.6 % (Yang et al. 2012). Thus, the prominent stability in the horizontal direction of biocrusts may exert a profound effect on the C factor in erosion models.

In this study we investigate the raindrop kinetic energy sustained by biocrusts of different successional stages by using the simulated single drop rainfall method. The potential influence of abiotic factors, including moisture, slope gradients, soil texture and seasonal variation on the resistance capacity of biocrusts is quantified. Thus, the purpose of our study is to resolve the erosion controlling capacities of biocrusts from an energy point of view, which may provide fundamental data for a first biocrust-considering erosion model.

Materials and methods

Study area

This study was conducted in the hilly Loess Plateau region in the northern Shaanxi province of China. The mean altitude is approximately 1,200 m, but there is significant topographic variation with typical loess hills and gully landforms. The region has a semiarid continental climate with a mean annual temperature of 7.8–8.8 °C. Mean monthly temperatures range from 22.5 °C in July to −7 °C in January. The average annual precipitation is 400–505 mm with ~60–70 % of it falling during heavy summer monsoon storms between June and September. On average, there are 157 frost-free days and 2,415 h of sunshine per year. In the region, the soil is made up by loess, which has an approximate thickness of 50–80 m and a uniform soil texture, being classified as *Calciustepts* in Chinese soil taxonomy. The soil has little resistance against erosion and used to be lost at a rate of about 10,000–12,000 Mg km^{-2} $year^{-1}$ before 1999 (Liu 1999; Shi and Shao 2000). The zonal vegetation of the region is warm shrub and meadow steppe, which is mostly dominated by *Rosa xanthina, Rubus parvifolius*, *Sophara viciifolia*, *Bothriochloa ischemum*, *Artemisia sacrorum*, *A. giralaii*, *Stipa bungeana* and *Lespideza* sp.

Cyanobacterial crusts may already form in the first year after cropland has been abandoned in this region. Mosses, which are also dominant biocrust constituents, mostly appear in the fourth year after revegetation, and their density and coverage increases with time since revegetation. The coverage of mosses within biocrusts could be up to 80 % on north-facing slopes (Zhao et al. 2006). Eight moss species, i.e. *Didymodon tectorum*, *D. vinealis, Bryum argenteum, B. caespiticium, B. arcticum, Trichostomum crispulum, Crossidium squamiferum,* and *Aloina rigida* were identified in the biocrust community (Zhang et al. 2007), but in most cases *Didymodon tectorum* and *D. vinealis* were the dominant species. Lichens start to establish 10 years after revegetation with eighteen species being determined within biocrusts of the region. Coverage, however, only rarely reaches up to 10 % (Zhao, unpublished). Therefore, response of lichen crusts to erosive forces was not considered in the study.

Twenty-six species of cyanobacteria, belonging to 13 genera and five families were identified in the biocrust communities of the study region (Yang et al. 2013). *Oscillatoriaceae* and the genus *Oscillatoria* were dominant and filamentous cyanobacteria accounted for 87 % (Yang et al. 2013).

Equipment and operation

The single drop simulated rainfall method was applied to test the response of biocrusts to raindrop erosive force. The equipment included a single raindrop simulator and a sieve used to support the biocrust samples. The single raindrop simulator consisted of a water container, a flow rate controller and a syringe needle. Airless distilled water was used as rainwater to keep the needle from blocking. The net height of the raindrops falling was 150 cm. The diameter of the raindrops was 4 mm and the mass of one raindrop was about 0.05 g. The raindrop frequency was one drop per second.

Prior to each experiment, the container was filled with airless distilled water and weighed (W_1). After the sample was put on the sieve, the rainfall simulator was started. As soon as the biocrust started to break, the rainfall simulator was stopped and the remaining water in the container (W_2) was weighed. Thus, the total mass of the raindrops could be calculated as

$$M_{rain} = W_1 - W_2. \tag{1}$$

According to Morgan (2005) the kinetic energy of one raindrop is

$$E = \frac{1}{2} m_{raindrop} V^2. \tag{2}$$

Thus, the accumulated kinetic energy of raindrops was

$$E = \frac{1}{2} \Sigma m_{raindrop} \quad V^2 = \frac{1}{2} M_{rain} V^2, \tag{3}$$

with E is the kinetic energy of raindrops [J], $m_{raindrop}$ is the mass of one raindrop [kg], M_{rain} is the total mass of raindrops [kg], V is the Velocity of raindrop when hitting the biocrusts [m/s] According to a relationship between velocity and diameter of simulated raindrops, the velocity of raindrops with a diameter over 1.9 mm could be calculated according to Wu (1988):

$$V = 4.8 \left[D \left(1 - e^{-0.85H/D} \right) \right]^{0.5} \tag{4}$$

with D is the diameter of raindrop [mm], here: 4 mm, H is the net height of the raindrop falling [m], here: 1.5 m, Thus, the instantaneous velocity of the simulated raindrops was

$$V = 5.02 \text{ m/s} \tag{5}$$

Sample collection and preparation

In order to study the raindrop erosivity of different crust successional stages, six replicates each of bare soil and six successional stages, as determined by moss coverage, were collected between June and September 2010 (Table 1). Eighty samples each of dark cyanobacterial crust (the common cyanobacterial crust) and 60 % moss covered crust, (most abundant moss-dominated crust) were sampled to investigate the impact of moisture. Ten replicates each of cyanobacteria- and 60 % moss-covered crust were collected on sandy, silty, and loamy soil to test the effect of soil texture on raindrop erosivity. An additional 80 samples of 60 % moss covered biocrusts were used to study the impact of slope at eight different gradients. The above two groups of samples were collected between June and September 2011. Finally, three times ten replicates each of dark cyanobacterial

Table 1 Characteristics of the sampled biocrust plots, consisting of rehabilitation age, slope gradient, slope aspect, plant coverage, dominating vascular plants and biocrust cover values

Biocrust type	Rehabilitation age (years)	Slope gradient (°)	Slope aspect	Plant coverage[a] (%)	Dominating vascular plants	Biocrust coverage[a] (%)
Light cyanobacteria crust	<1	10	45°EN45°	40 ± 3.7	*Artemisia capillaris*	90 ± 2.4
Dark cyanobacteria crust	3	0	/	40 ± 6.7	*A. capillaris*	88 ± 4.5
20 % Moss covered crust	5	18	E	48 ± 2.9	*A. capillaris, Stipa bungeana,*	86 ± 1.5
40 % Moss covered crust	18	25	45°EN45°	67 ± 4.4	*A. sacrorum, Astragalus melilotoides*	87 ± 0.9
60 % Moss covered crust	20	7	W	70 ± 3.5	*A. sacrorum,*	86 ± 1.0
80 % Moss covered crust	15	17	N	59 ± 4.5	*A. sacrorum*	73 ± 2.3

Coverage values of plants and biocrusts are given as mean values ± SE

[a] Most of the biocrusts were collected on four independent plots except 40 % moss covered crust, which was collected on three independent plots

and 60 % moss covered biocrust samples were collected from the same plots in May (pre-monsoon), August (monsoon) and November (post-monsoon) 2011 to investigate the impact of season (Table 2).

All samples were collected in plastic petri dishes of 9 cm diameter and 1 cm depth. After collection, the samples were air dried at room temperature and room light. Prior to testing, each of the biocrust samples was quartered. Then, one quarter was used to test the resistance capacity against raindrop erosive forces. The other three quarters were used to analyze biomass, physical, and chemical properties of the biocrust. Biomass of cyanobacteria and mosses, moss coverage, chemical and physical characteristics of the samples are listed in Table 1.

Experimental design

In order to determine the response of biocrusts to the raindrop erosive force and its influencing factors, five single-factor sub-experiments were designed. They were (1) response of biocrusts of different successional stages; (2) impact of soil moisture; (3) impact of slope gradients; (4) impact of substrate soil texture, and (5) relevance of seasons for the response of biocrusts to raindrop erosive forces. The details of each sub-experiment were as follows:

(1) Six successional stages of crusts (n = 6) were randomly tested for their resistance against raindrop erosive forces. Saturated biocrust samples (100 % field water holding capacity, FWHC) were used in the experiment and the slope gradient was set to 15°. After this experimental part, the biocrusts were removed and the measurements were repeated with the same measurement parameters on the scalped

Table 2 Biomass of biocrust types

Biocrusts	Light cyanobacteria crust	Dark cyanobacteria crust	20 % Moss covered crust	40 % Moss covered crust	60 % Moss covered crust	80 % Moss covered crust
Biomass grades	1	2	3	4	5	6
Biomass[a]	3.32 ± 0.20 Chl *a* μg/g soil	3.73 ± 0.28 Chl *a* μg/g soil	2.03 ± 0.15 g/dm^2	2.49 ± 0.24 g/dm^2	3.70 ± 0.20 g/dm^2	4.73 ± 0.35 g/dm^2

Determination as chlorophyll *a* content per sample dry weight in cyanobacteria-dominated and as dry weight of moss plants per area in moss-dominated crusts

[a] Biomass of cyanobacterial crust was the content of chlorophyll *a* per unit soil mass, the biomass of moss crust was the biomass of moss per square decimeter

samples. The reduction of kinetic energy caused by biocrust growth was calculated according to the formula

$$E_{red} = \left(\left(E_{crust} - E_{scalped}\right)/E_{crust}\right) \times 100 \quad (6)$$

with E_{red} is the reduction of raindrop kinetic energy by biocrust [%], E_{crust} is the accumulated raindrop energy of samples with biocrust [J], $E_{scalped}$ is the accumulated raindrop energy of scalped samples [J]

(2) The impact of soil moisture was investigated on dark cyanobacterial and 60 % moss covered biocrusts. Eight moisture content values, i.e. air-dry, 20, 40, 50, 60, 70, 80 and 100 % FWHC were set up in the experiment and ten replicates of each crust type were measured at each water content. Response of biocrust erosivity to different water contents was randomly measured at a slope gradient of 15°.

(3) The influence of slope gradients on the raindrop erosivity was investigated on 60 % moss-covered biocrusts. The slope gradients were set to 0°, 5°, 10°, 15°, 20°, 25° and 30° according to the ground slope range in the region. Saturated biocrust samples were used in the experiment and the response under different slope gradients was randomly examined with ten replicates at each slope gradient.

(4) Dark cyanobacterial and 60 % moss covered biocrusts developed on sandy, silty and loamy soil were used to investigate the influence of substrate soil texture. Ten replicates each of the two saturated crust types on the three different substrates were measured at a slope gradient of 15°.

(5) Biocrusts collected during pre-monsoon, monsoon and post-monsoon time were examined to determine an influence of season on their response to raindrop erosivity. Ten replicates each of saturated dark cyanobacterial and 60 % moss covered biocrusts were tested at a slope gradient of 15°.

Statistical analyses

Data were examined for normality by using the Kolmogorov–Smirnov test and, when necessary, logarithmic transformations were performed. Homogeneity of variance was ensured using the Levene test. Then, one-way ANOVA tests were performed to detect significant differences between the mean values of accumulated raindrop kinetic energy sustained by biocrusts in each treatment by using the SPSS 12.0 statistical software package (SPSS, USA), followed by Fisher's LSD post hoc test. Statistical significance was defined as $P < 0.05$.

Results

Influence of successional stage and biomass on the raindrop erosivity

As expected, the resistance of soil against raindrop erosivity was significantly increased by the formation of biocrusts (Fig. 1) and there were significant differences depending on the successional stage (Fig. 2). The maximum erosive forces sustained by dark cyanobacterial crusts were 0.93 J, which was 15-fold higher than on local bare soil (0.06 J) (Fig. 1). The raindrop kinetic energy sustained by 60 % moss covered biocrusts (20.18 J) was 21-fold higher compared to dark cyanobacterial crusts and 342 fold higher compared to bare soil.

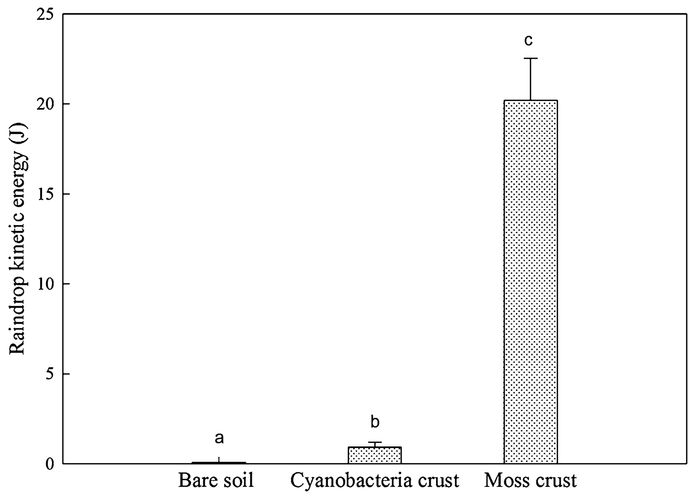

Fig. 1 Raindrop kinetic energy sustained by bare soil, dark cyanobacteria-dominated crust and 60 % moss-covered crust. *Different letters* indicate significant differences ($P < 0.05$; bare soil: n = 6; cyanobacteria crust: n = 6; moss crust: n = 6)

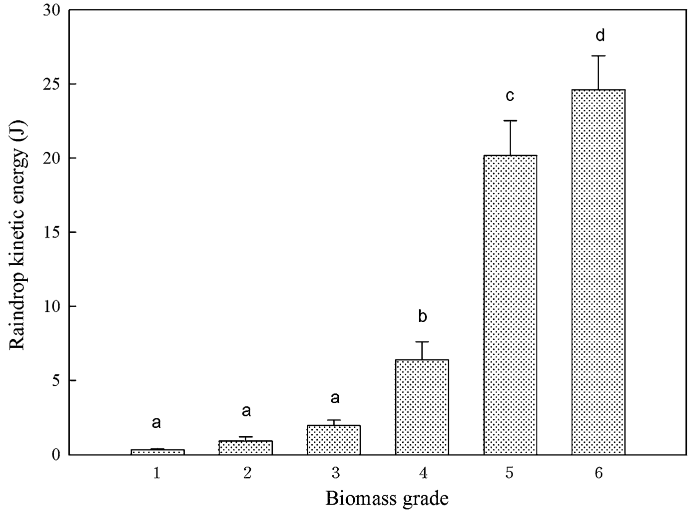

Fig. 2 Raindrop kinetic energy sustained by biocrusts of different biomass grades. Explanation of biomass grades is given in Table 2. *Different letters* indicate significant difference ($P < 0.05$; n = 6)

Higher biomass values of biocrusts with similar species composition tended to improve their resistance capacity, as measured for dark cyanobacterial crusts (0.93 J) compared to light cyanobacterial crusts (0.32 J), but no significant relationship could be defined. In moss-dominated crusts, the accumulated kinetic energy sustained by them increased significantly with biomass, as crusts with 20 % moss coverage reached 1.98 J, those with 60 % attained 20.18 J. and crusts with 80 % coverage sustained an accumulated kinetic

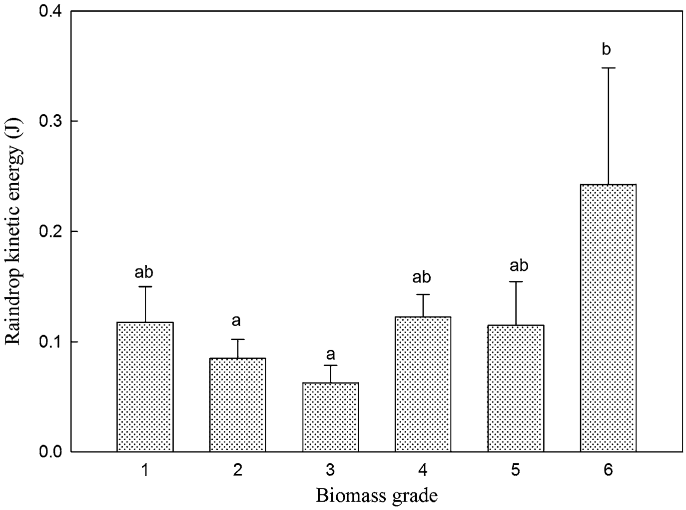

Fig. 3 Raindrop kinetic energy sustained by scalped biocrust samples of different biomass grades. Explanation of biomass grades is given in Table 2. *Different letters* indicate significant differences ($P < 0.05$; $n = 6$)

energy of 24.59 J. Generally, the resistance capacity of biocrusts increased with the successional stage of the biocrust (Fig. 2).

When the biocrusts were removed, the erosion resistance of all samples decreased dramatically and no obvious pattern could be detected between the substrates (Fig. 3). Based on the raindrop kinetic energy sustained by intact and scalped biocrusts, the average reduction of the sustained kinetic energy by biocrusts could be calculated (Fig. 4). Here, significant differences between biocrusts of grade 1 as compared to grade 2–6 become obvious.

Influence of moisture on raindrop erosivity

The accumulated kinetic energy sustained by biocrusts of different water content is shown in Fig. 5. For both cyanobacterial and moss crusts, only the kinetic energy sustained by the air dried samples was significantly higher compared to that of all the wetted samples. Neither cyanobacterial nor moss crusts showed significant difference in resistance capacity between the seven moisture levels. Generally, moss-dominated crusts had significantly higher resistance capacity values, being ~19-fold higher compared to those of cyanobacterial crusts.

Influence of slope gradient on raindrop erosivity

The accumulated kinetic energy sustained by 60 % moss covered biocrusts at different slope gradients increased significantly with increasing slope gradients as shown in Fig. 6. At slope gradients of 30°, resistance capacity of moss crusts with 60 % coverage was highest with values of 33.8 J being reached on average.

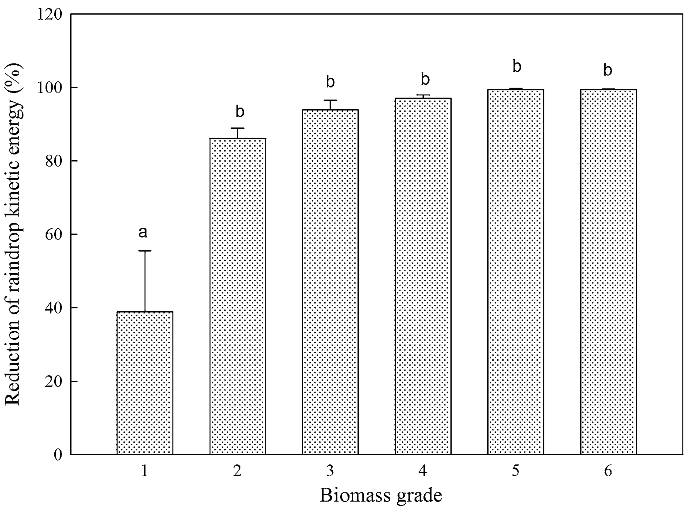

Fig. 4 Average reduction of raindrop kinetic energy by biocrusts of different biomass grades. Explanation of biomass grades is given in Table 2. *Different letters* indicate significant difference ($P < 0.05$, $n = 6$)

Influence of soil texture on raindrop erosivity

The accumulated raindrop kinetic energies sustained by cyanobacteria and moss-dominated crusts growing on sandy, silty, and loamy soils revealed large differences as shown in Fig. 7. Cyanobacteria-dominated crusts on sand had significantly lower erosion resistance values (0.17 J) compared to those growing on silt and loam (0.32 and 0.28 J), which were not significantly different from each other. Resistance capacity of moss dominated crusts was generally much higher and reached highest values on sand (~57.6 J) as compared to those on silt and loam being similar to each other (20.2 and 18.1 J).

Influence of seasonal variation on raindrop erosivity

The accumulated raindrop kinetic energy sustained by biocrusts displays differences between seasons (Fig. 8). All three crust types had significantly higher resistance values during monsoon and post-monsoon as compared to pre-monsoon. There were significant differences between raindrop erosivity values of the three crust types with cyanobacteria-dominated crusts reaching lowest values followed by moss-dominated crusts with 50 and 80 % coverage (Fig. 8).

Discussion

Influence of community composition and biomass

Biocrusts are well known for their protection of soil against water and wind erosion (Warren 2003; Eldridge and Greene 1994a). Raindrop splash is the first step of water erosion and the kinetic energy of falling raindrops not only detaches but also provides soil particles to the ensuing erosion process (Morgan 2005). Our study revealed that erosion

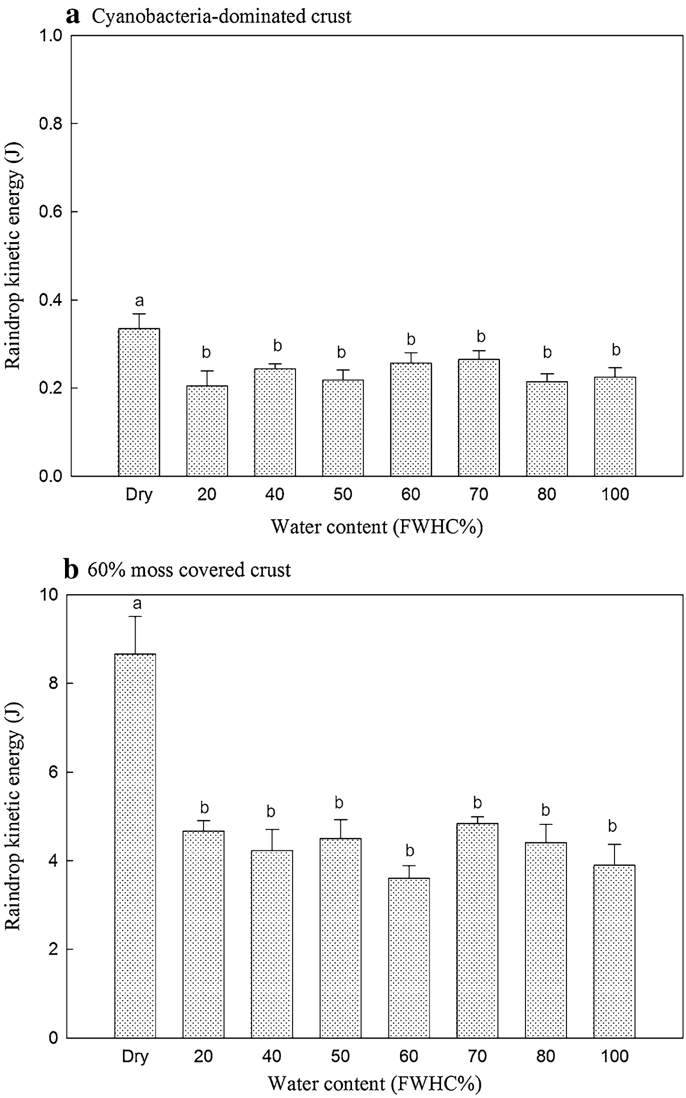

Fig. 5 Raindrop kinetic energy sustained by (**a**) cyanobacteria-dominated crusts and (**b**) 60 % moss covered crusts at different water contents. *Different letters* indicate significant differences ($P < 0.05$; $n = 10$)

resistance of soils is dramatically increased by the formation of biocrusts, being influenced by several parameters. Both biocrust community composition and biomass had significant effects on erosion resistance values. While cyanobacterial crusts raised the resistance capacity by a factor of 15 compared to bare soil, 60 % moss covered crusts enhanced it by a factor of 342 compared to bare soil and by a factor of 21 compared to cyanobacterial crusts. These differences were caused by different crust types, as after scalping of the crusts, the values had decreased dramatically and revealed no differences anymore. More than 99 % of the raindrop kinetic energy was buffered by biocrusts with moss coverage

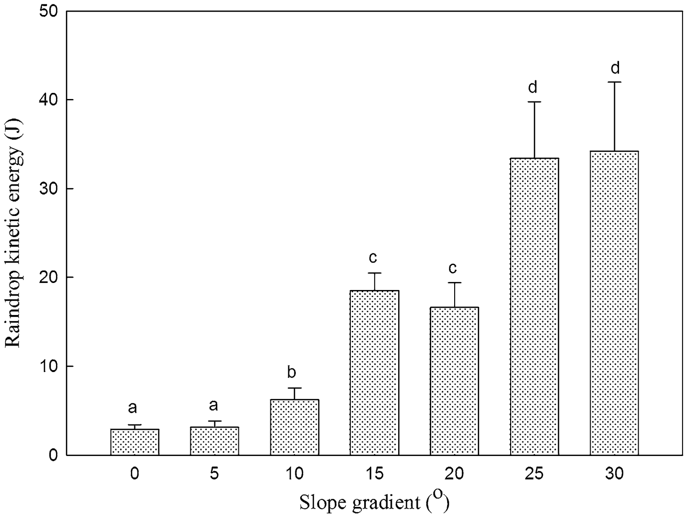

Fig. 6 Raindrop kinetic energy sustained by 60 % moss covered crusts at different slope gradients. *Different letters* indicate significant differences ($P < 0.05$; $n = 10$)

above 60 % (i.e. 20.18 vs. 0.12 J on bare soil), which reflects the substantial protective role of biocrusts during splash erosion processes.

Most cyanobacteria, though often the dominant components of biocrusts in many arid and semiarid regions, are tiny organisms, which live within the uppermost millimeters of the soil (Belnap et al. 2003). Thus, the protective role of cyanobacterial crusts is mainly due to soil aggregation enhanced by polysaccharide exudates and physical bonding of cyanobacterial filaments. These influence erodibility and provide considerable erosion resistance. Compared to mosses and lichens, either the amount of polysaccharide exudates or the bonding force of the filaments of cyanobacteria was low. Hence, the tolerance to raindrop erosivity was limited. In contrast to that, mosses have both above- and below-ground structures including stem- and leaf-like structures and rhizoids of varying size (Goffinet and Shaw 2009). Stem- and leaf-like structures of mosses may offer an effective buffering agent for raindrops reducing their velocity before they strike the soil surface. Belowground, the dense rhizoids weave soil particles together, enhancing stability of soil aggregates and resistance to shear stresses (Yang et al. 2012).Other studies have also demonstrated that the moss crusts are much more effective in stabilizing the soil as compared to cyanobacterial crusts (Gao et al. 2013; Chamizo et al. 2012). Similar to vascular plant vegetation, the protective function was positively correlated with moss coverage and biomass.

Factors influencing raindrop erosivity

During a given rainfall event, rainfall splash erosion is mainly depending on soil erodibility, itself being influenced by soil properties, slope steepness and the antecedent soil water content apart from characteristics of the rainfall (Morgan 2005). As expected, results of this study showed that all factors investigated, i.e. moisture, slope gradients, soil texture and seasonal variation had significant impact on the resistance capacity of biocrusts to raindrop erosivity.

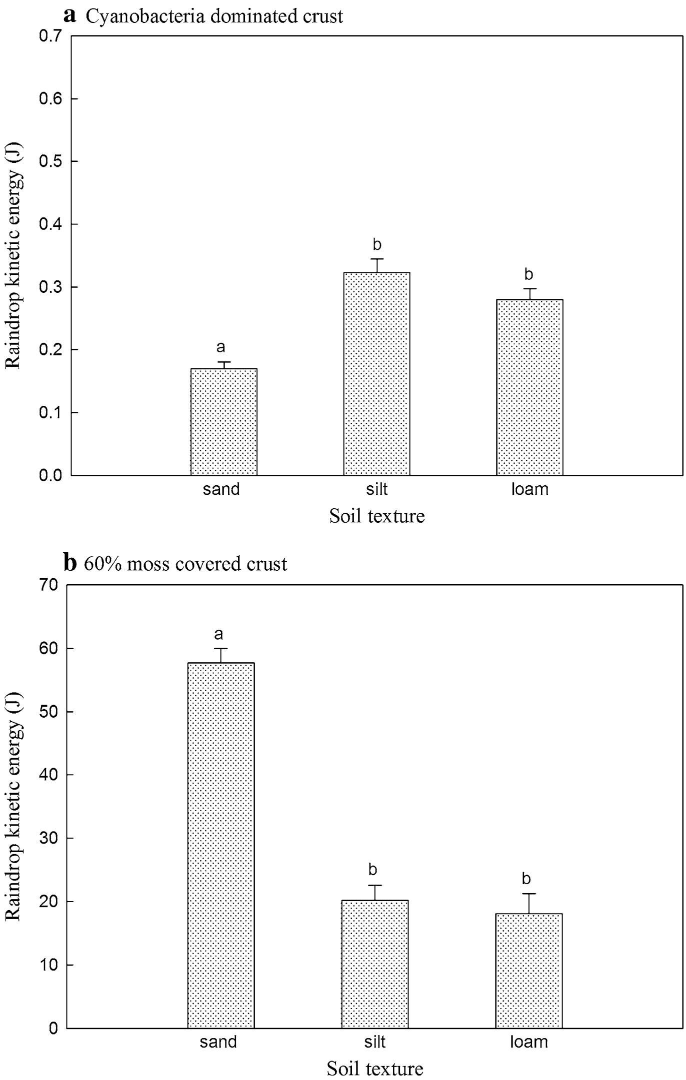

Fig. 7 Raindrop kinetic energy sustained by (**a**) cyanobacteria-dominated crust and (**b**) 60 % moss covered crust on different substrates. *Different letters* indicate significant differences ($P < 0.05$; $n = 10$)

Moisture and seasonality

As moisture influences soil properties such as hardness, cohesion, aggregate stability and erodibility, it is considered as an important factor influencing raindrop erosivity (Morgan 2005). In addition, soil moisture may alter the stability of biocrusts by modifying the activity status of the poikilohydric organisms within them. Our study revealed that, indeed, dry biocrusts have significantly higher resistance capacities compared to wet samples. However, there were no differences between wet crusts of different water content. The difference between wet and dry crusts was much more pronounced in moss- as compared

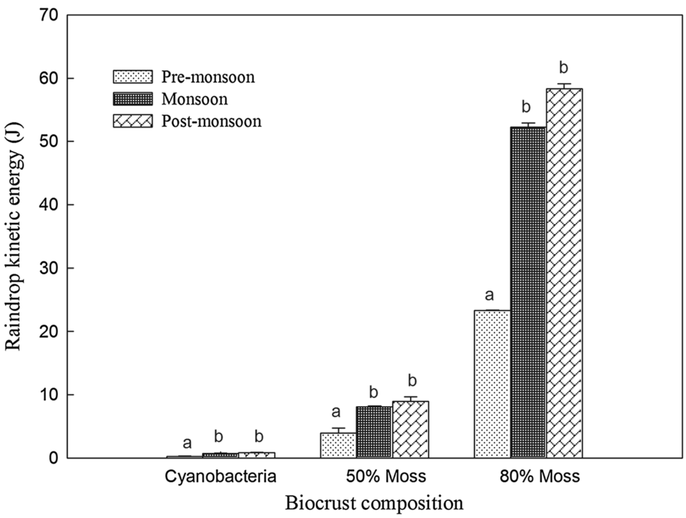

Fig. 8 Seasonal variation of raindrop kinetic energy sustained by different biocrust types. *Different letters* indicate significant differences between seasons ($P < 0.05$; $n = 10$)

to cyanobacteria-dominated crusts. Here, one has to keep in mind, that the FWHC of moss crusts is much greater than that of cyanobacteria-dominated crusts (Goffinet and Shaw 2009), causing much larger differences in water content between dry and wet moss as compared to cyanobacterial crusts. While the cyanobacteria-dominated crusts showed approximately 0.1 J difference in the accumulated kinetic energy between the dry and wet samples, the moss crusts revealed a difference of about 4 J.

In our study, resistance capacity of the wet biocrusts was tested soon after the dry samples were watered to the target moisture content. It might be possible that the hydration period may not have been long enough to completely influence the activity of the organisms, possibly resulting in the insignificant difference between biocrusts of differing moisture levels. However, if the biocrusts experienced different water contents for a long period, as e.g. several days, the difference in water regime may cause growth and an alteration of the physiological activity of organisms, which may then cause differences in erosion resistance, and may explain the seasonal variation in erosion resistance (Fig. 7). Biocrusts from the same plot showed significantly higher resistance capacity during the monsoon and the post-monsoon compared to the pre-monsoon. This effect is in accordance with observations by Karnieli et al. (2002), who observed that the spectral signal of biocrusts decreased during the dry season, indicating a weakening of the crusts during that time.

Soil texture

Soil texture is a fundamental property, which is known to have a profound influence on soil erodibility (Morgan 2005). For biocrusts, the texture of substrate soil often also influences the species composition and biomass (Belnap et al. 2003; Eldridge and Greene 1994a), which may cause a variation in the resistance capacity to raindrop splash. Results of our study confirmed this assumption. Biocrusts growing on differently textured soil responded dramatically different to erosive forces. Cyanobacterial crusts on sandy soil sustained significantly lower raindrop kinetic energies as compared to those growing on silt and loam, which may be caused by the lower resistance against detachment of the coarser particles of the sandy substrate (Morgan 2005). For moss crusts, which in general had a higher stability, sustained kinetic energies were higher on sand as compared to silt and loam. The poor stability of sand causes burial of a considerable proportion of the moss biomass beneath the soil surface. This subsurface tissue increases erosion resistance considerably (Jia et al. 2008).

Slope steepness

Slope steepness may alter the raindrop erosivity due to the changed angle between the soil surface and raindrop striking direction (Jiang and Liu 1989; Morgan 2005). Almost all studies up to now have demonstrated threshold angles for splash erosion, whereas the values were not always the same: for bare soil, the erodibility increased with increasing angle until the threshold angle was reached (Jiang and Liu 1989; Morgan 2005; Liu et al. 2011). In our case, however, the resistance capacity of moss crusts to raindrop erosivity correlated with slope gradients. This might be caused by the angle between the moss stems and the raindrop striking direction. At larger angles, the moss stems may shield the soil more effectively against vertical raindrop slash causing higher erosion resistance values. This shielding effect of mosses can also be observed on cliffs at the natural habitat, where moss-dominated crusts on steep cliffs prevent an erosion of the substrate and the underlying soil.

Linkage of biocrust data to erosion models

Biocrusts are a crucial factor influencing soil erosion in arid and semiarid regions where the coverage of higher plants is limited (Warren 2003; Eldridge and Greene 1994a). Whereas numerous studies have demonstrated that soil loss is dramatically reduced by biocrusts (Eldridge and Greene 1994a; Belnap and Gillette 1997; Zhao and Xu 2013), it is still problematic to link the effectiveness of biocrusts to existing erosion models. Theoretically, the effects of biocrusts may be added to existing erosion models within the soil erodibility factor (K) or the cover-management factor (C) or both. Bowker et al. (2008) concluded that for the biocrust soils the C factor was considerably more influential than the K factor. Namely, the physical protection of biocrust cover was more important than its influence on soil properties. Given this, it was impossible to link biocrusts to the models unless the quantitative relationship between soil erosion and biocrust development was determined.

Aiming at this knowledge gap, we investigated the raindrop erosivity of biocrusts as compared to bare soil from an energy point of view. Our study revealed the quantitative relationship between the biocrusts' successional stages and their potential resistance against raindrop erosive energy as well as the influences of some factors, such as land slope, moisture, soil texture and seasonal activity. These results provide first baseline data for biocrust-considering erosion models by expressing biocrust stability in the form of erosion energy data. Thus, our study provides a new method to incorporate the effects of biocrusts on soil stability in soil erosion models. In a next step, the quantitative relationship between soil loss and biocrust development status need to be determined in a comprehensive consideration of soil parameters, topography and biological activity of the biocrusts.

Conclusion

Soil surface resistance capacity to raindrop erosivity was significantly enhanced by biocrusts. The raindrop kinetic energy provided a bridge between biocrust successional stages, composition and biomass on the one and soil erodibility expressed by the C factor in the erosion models on the other hand. While the accumulated raindrop kinetic energies sustained by the dark cyanobacterial crust were 0.93 J, these sustained by 80 % moss crusts were be 24.59 J, which was approximately 15 and 417 times higher than the values of the local bare soil.

The resistance capacity of biocrusts to raindrop kinetic energy was related to soil texture, seasonal variation and slope gradients. The accumulated raindrop kinetic energy sustained by cyanobacterial crusts was lower for crusts on sand as compared to those growing on silt or loam. Moss crusts had significantly higher resistance capacities on sand as compared to those on silt or loam. The resistance capacities of biocrusts during monsoon and post-monsoon were significant higher than that of pre-monsoon. The resistance capacity of biocrusts to raindrop erosivity increased with increasing slope gradients. Our results demonstrate that it is possible to build biocrust-considering erosion models by combining biocrust stability with erosion energy. Now, comprehensive data on soil parameters, topography and biological activity are necessary to finally include biocrusts, which are of dramatic importance in soil erosion processes, in existing or newly designed soil erosion models.

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References

Belnap J, Gillette DA (1997) Disturbance of biological soil crusts: impacts on potential wind erodibility of sandy desert soils in southeastern Utah. Land Degrad Dev 8:355–362

Belnap J, Büdel B, Lange OL (2003) Biological soil crusts: characteristics and distribution. In: Belnap J, Lange OL (eds) Biological soil crusts: structure, function, and management. Springer, Berlin, pp 3–30

Booth WE (1941) Algae as pioneers in plant succession and their importance in erosion control. Ecology 22:38–46

Bowker MA, Belnap J, Chaudhary VB, Johnson NC (2008) Revisiting classic water erosion models in drylands: the strong impact of biological soil crusts. Soil Biol Biochem 9:2309–2316

Chamizo S, Cantón Y, Miralles I, Domingo F (2012) Biological soil crust development affects physicochemical characteristics of soil surface in semiarid ecosystems. Soil Biol Biochem 49:96–105

Deng L, Shangguan ZP, Li R (2012) Effects of the grain-for-green program on soil erosion in China. Int J Sediment Res 27:120–127

Dojani S, Büdel B, Deutschewitz K, Weber B (2011) Rapid succession of biological soil crusts after experimental disturbance in the Succulent Karoo, South Africa. Appl Soil Ecol 48:263–269

Eldridge DJ, Greene RSB (1994a) Microbiotic soil crusts: a review of their roles in soil and ecological processes in the rangelands of Australia. Aust J Soil Res 32:389–415

Eldridge DJ, Greene RSB (1994b) Assessment of sediment yield by splash erosion on a semi-arid soil with varying cryptogam cover. J Arid Environ 26:221–223

Faust WF (1970) The effect of algal-mold crusts on the hydrologic processes of infiltration, runoff, and soil erosion under simulated conditions. MS Thesis, University of Arizona, Tucson

Faust WF (1971) Blue-green algal effects on some hydrologic processes at the soil surface. In: Hydrology and water resources in Arizona and the southwest, Proceedings of the Arizona Section, American Water Resource Association, and Hydrology Section Arizona Academy of Sciences, Tempe, Arizona, pp 99–105

Fletcher JE, Martin WP (1948) Some effects of algae and molds in the rain-crust of desert soils. Ecology 29:95–100
Gao LQ, Zhao YG, Qin NQ, Zhang GX (2013) Effects of biological soil crust on soil erodibility in hilly Loess Plateau Region of Northwest, China. Chin J Appl Ecol 1:105–112
Gaskin S, Gardner R (2001) The role of cryptogams in runoff and erosion control on bariland in the Nepal Middle Hills of the Southern Himalaya. Earth Surf Process Landf 26:1303–1315
Goffinet B, Shaw AJ (2009) Bryophyte biology, 2nd edn. Cambridge University Press, Cambridge
Jia RL, Li XR, Liu LC, Gao YH, Li XJ (2008) Responses of biological soil crusts to sand burial in a revegetated area of the Tengger Desert, Northern China. Soil Biol Biochem 40:2827–2834
Jiang ZS, Liu Z (1989) Effect of rainfall factors and slope on splash erosion. Acta Conserv Soil et Aquae Sin 2:29–35
Karnieli A, Gabai A, Ichoku C, Zaady E, Shachak M (2002) Temporal dynamics of soil and vegetation spectral responses in a semi-arid environment. Int J Remote Sensing 23(19):4073–4087
Leys JF, Eldridge DJ (1998) Influence of cryptogamic crust disturbance to wind erosion on sand and loam rangeland soils. Earth Surf Process Landf 23:963–974
Liu G (1999) Soil conservation and sustainable agriculture on the Loess Plateau: challenges and prospective. Ambio 28:663–668
Liu HP, Fu SH, Wang XY et al (2011) Effect of slope gradient on raindrop splash erosion. Acta Pedo Sin 3:479–486
McCalla TM (1946) Influence of some microbial groups on stabilizing soil structure against falling water drops. Soil Sci Soc Am Proc 11:260–263
Morgan RPC (2005) Soil erosion and conservation, 3rd edn. Blackwell, Oxford, p 304
Shi H, Shao MA (2000) Soil and water loss from the Loess Plateau in China. J Arid Environ 45:9–20
Uchida E, Xu J, Rozelle S (2005) Grain for green: cost-effectiveness and sustainability of China's conservation set-aside program. Land Econ 81:247–264
Wang R, Zhu QK, Bu N, Qin W, An YC (2010) Study on physicochemical properties of biological soil crusts in the hilly–gully regions of the Loess Plateau. Arid Zone Res 3:401–408
Warren SD (2003) Biological soil crusts and hydrology in North American deserts. In: Belnap J, Lange OL (eds) Biological soil crusts: structure, function, and management. Springer, Berlin, pp 329–339
Wu KA (1988) An improvement to the falling velocity formula of the larger-diameter raindrop in the simulated rainfall. Acta Conserv Soil et Aquae Sin 1:82–86
Xu MX, Zhao YG, Liu G et al (2006a) Identification of soil quality factors and indicators for the Loess Plateau of China. Soil Sci 171:400–413
Xu MX, Zhao YG, Liu G et al (2006b) Soil quality indices and their application in the hilly Loess Plateau region of China. Aust J Soil Res 44:245–254
Yang K, Zhao YG, Ma XX (2012) Water stability of biological soil crusts in hilly regions of Loess Plateau, Northwest China. Chin J Appl Ecol 1:173–177
Yang LN, Zhao YG, Ming J et al (2013) Cyanobacteria diversity in biological soil crusts from different erosion regions on the Loess Plateau: a preliminary result. Acta Ecol Sin 14:4416–4424
Zhang MX, Zhao YG, Chen Y (2007) Mosses growing on rehabilitation lands in Ansai County of Northern Shaanxi Province. Chenia 9:343–348
Zhao YG, Xu MX (2013) Runoff and soil loss from revegetated grasslands in hilly Loess Plateau region, China: influence of biocrust and plant patches. J Hydrol Eng 18:387–393
Zhao YG, Xu MX, Wang QJ, Shao MA (2006) Physical and chemical properties of biological soil crust on rehabilitation grassland in the Hilly Loess Plateau of China. Chin J Appl Ecol 17:1429–1434
Zheng M, Cai QG, Chen H (2007) Effect of vegetation on runoff-sediment yield relationship at different spatial scales in hilly areas of the Loess Plateau, North China. Acta Ecol Sin 9:3572–3581