

# Chapter 16

## Biological Soil Crusts as Soil Stabilizers

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### 16.1 Introduction

Soil movement via aeolian and fluvial processes provides important local, regional, and global biogeochemical linkages between the atmosphere, hydrosphere, biosphere, and pedosphere (Schlesinger et al. 1990; Syvitski 2003). However, this soil redistribution has had detrimental and often irreversible consequences in the past that are likely to continue into the future (Bridges and Oldeman 1999; Lal 2001; Valentin et al. 2005). Dryland regions are particularly vulnerable to soil erosion because of the low levels of vascular vegetation, soil moisture, and soil organic matter. In addition, many soils are a mix of sand and fine particles that are especially prone to wind erosion. As a result, erosion resistance depends mostly on the presence of physical or biological soil crusts to stabilize the large exposed interspaces between plants (Sivakumar 2007; Belnap 2003). Because drylands are inhabited by one-third of the world's population, human-related disturbances often disrupt biocrusts (UNDP/UNSO 1997; Eldridge and Belnap 2003), with the result that  $\sim 24$  million  $\text{km}^{-2}$ , or approximately 17.5 % of the global land area, is being degraded by wind and water erosion (Williams and Balling 1996; Bullard and McTainsh 2003).

In dryland regions, soil loss can greatly exceed formation rates, as it can take thousands of years to form a few centimeters of soil (Pillans 1997; Cuff and Goudie 2009). Eroded soils are less fertile, as wind and water can winnow out the fine clay

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particles to which nutrients are adsorbed, leaving behind coarser soils with fewer nutrients (Neff et al. 2005). Soils are often very shallow in desert areas and can be completely stripped away when soil protection is lost (Jayne Belnap, personal observation). Eroded soils are often deposited in streams by either wind or water, negatively impacting water quality. In addition, dust deposited on nearby mountains increases the melt rate of the snowpack, decreasing both late season water and the total amount of water entering streams (Painter et al. 2010). Dust can also place human health at risk (e.g., respiratory disease, highway fatalities).

In this chapter, we will explore the role that biocrusts play in preventing wind and water erosion in dryland regions. We will emphasize studies that have occurred since 2000, as studies prior to that time were reviewed in Belnap (2003), Warren (2003a, b), and Belnap and Lange (2003). As almost all studies have found that biocrusts stabilize soils from both types of erosive forces, we will be focusing on the factors that influence the degree to which biocrusts confer resistance.

## **16.2 Biocrust Characteristics that Confer Resistance and Resilience to Soil Erosion**

The major biocrust characteristics that influence soil protection from wind and water erosion include the morphology of individual species, as well as the developmental stage and biomass of the biocrust community as a whole. The extent, intensity, and time since disturbance are also important, but these factors are reflected in the species composition and biomass of the biocrust community. Because these characteristics vary with climate, soils, and other factors, erosion resistance and resilience can vary within short distances.

### ***16.2.1 Species and Biocrust Developmental Stages Affect Resistance to Wind and Water Erosion***

There have been a substantial number of studies examining the effect of biocrusts on wind and water erosion. In almost all cases, biocrusts increase the resistance of soils to erosion. However, very few studies have addressed how individual species influence soil loss, and most have been wind tunnel studies. Fortunately, we have many more studies that have compared the differential protection offered by various levels of biocrust community development from both wind and water.

## 16.2.2 Individual Species Affect Resistance to Soil Loss

Biocrust development begins with the colonization of cyanobacteria and fungi. Hu et al. (2002) examined the stabilization capability of four filamentous cyanobacteria (*Microcoleus vaginatus*, *Phormidium tenue*, *Scytonema javanicum*, and *Nostoc* sp.) and one green alga (*Desmococcus olivaceus*), all species commonly found in early successional biocrusts. Using a wind tunnel run at 6 m s<sup>-1</sup>, they showed that *Microcoleus vaginatus* and *Phormidium tenue* needed the least biomass (0.6–1.3 and 1.4–2.3 mg chl a g<sup>-1</sup> dry soil, respectively) of all tested species to withstand this wind speed. The remaining species required substantially more biomass, with *Scytonema javanicum* needing 6.3–13.0 and *Nostoc* sp. 34.7–55.6, mg chl a g<sup>-1</sup> dry soil. *Desmococcus olivaceus* was unable to stabilize soils at any application rate. A blend of 80 % *Microcoleus vaginatus* and 5 % each of the other four species required less biomass to stabilize soils than an equal mix of the five species, again indicating the superiority of *Microcoleus vaginatus* in stabilizing soils.

Measuring threshold friction velocities (TFV, the wind speed at which soil particles are moved), this same study (Hu et al. 2002) showed that *Microcoleus vaginatus*, *Phormidium tenue*, and the *Microcoleus vaginatus*-dominated mix had higher TFVs than *Nostoc* sp., *Desmococcus olivaceus*, or the mix with equal proportions of the species. Similarly, McKenna-Neuman et al. (1996) found the cyanobacterium *Nostoc commune* or a mixture of the cyanobacteria *Nostoc commune* and a *Lyngbya* species was superior to the green alga *Chlamydomonas acidophila* in stabilizing soil surfaces. However, in contrast to this general pattern of cyanobacteria being better at stabilization of soils than green algae, the filamentous cyanobacterium *Lyngbya* sp. was the least resistant of the three species they tested (and, coincidentally, has a firm, narrow sheath that is not sticky; Burkhard Büdel, personal observation). Interestingly, Hu et al. (2002) found that small amounts of dust, when incorporated slowly into a *Microcoleus* biocrust, increased biocrust cohesion and thus resistance to wind erosion.

In another study, McKenna-Neuman and Maxwell (1999) examined the resistance of three monospecific fungal biocrusts (*Aureobasidium pullulans*, *Trichoderma harzianum*, and *Absidia corymbifera*), a cyanobacterial biocrust (*Nostoc commune*), and a green algal biocrust (*Chlamydomonas acidophila*). All three artificial fungal biocrusts were thicker and more resistant to wind erosion than the photoautotrophic biocrusts. The order of resistance was *Trichoderma harzianum* > *Absidia corymbifera* > *Aureobasidium pullulans* > *Nostoc commune* > *Chlamydomonas acidophila*. They also showed that the breakdown of biocrusts can occur either during a high-energy wind event or, surprisingly, by slow abrasion during chronic low-energy wind events (McKenna-Neuman et al. 1996; McKenna-Neuman and Maxwell 1999, 2002). Thus, biocrust integrity depends on growth rates in excess of the chronic loss as well as loss imposed by high-energy velocity wind events. The only study we could find on how individual microbial species influenced water erosion was Kidron

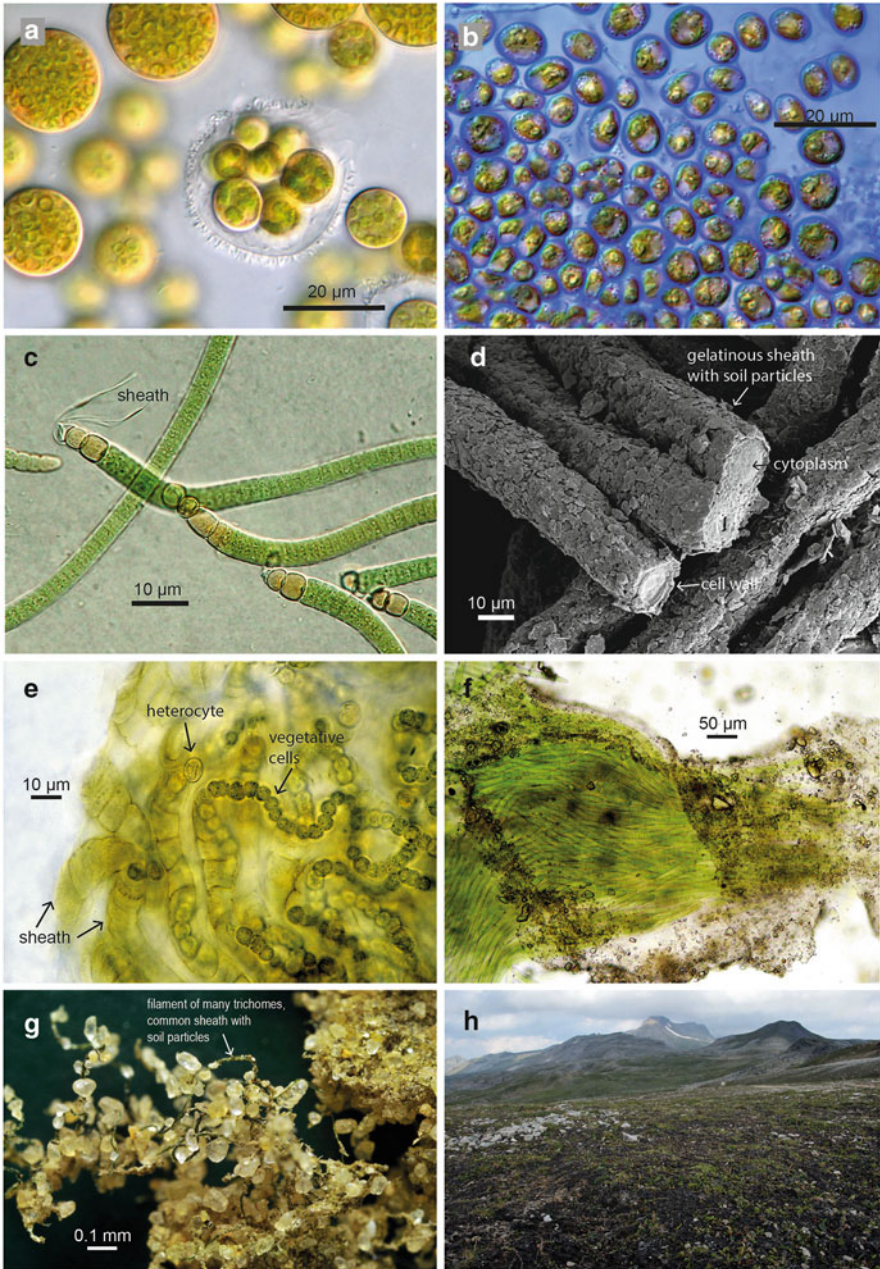
et al. (1999). Similar to the findings on wind erosion, they found *Scytonema* sp. to be more effective at stabilizing surfaces than *Nostoc commune*.

As mosses and lichens colonize biocrusts, wind resistance continues to increase. A wind tunnel study showed that biocrusts dominated by either the moss *Tortula ruralis* or *Pohlia nutans* were equally protective of the soil surface when exposed to sand-containing winds at 6 or 7.5 m s<sup>-1</sup> (McKenna-Neuman and Maxwell 2002). An additional and interesting finding of this study was that the breakdown of biocrusts, regardless of whether cyanobacterial or moss-dominated biocrusts, can result from a slow, constant abrasion of the biota as well as from acute wind events. Unfortunately, this was the only study that could be found looking at the resistance of individual moss or lichen species.

There are many ways in which species can vary in their ability to stabilize soils. For microbes, these include (1) size and strength of individual cells to enable resistance to abrasion and breakage; (2) ability to form filaments, giving the organism the ability to wrap around soil particles as well as connect them together into soil aggregates (Belnap and Gardner 1993); (3) amount of exo-polysaccharides secreted, as these provide the “glue” that enables the filaments to adhere to the soil particles and other organisms; (4) length of filaments, enabling them to cover more soil particles; (5) strength of cell linkages along the filament so the filaments do not break with stress; and (6) mobility in the soil, enabling the organism to both cover more soil particles with EPS and cells/filaments, as well as incorporate newly deposited material, thus avoiding death by burial and increasing the strength of the biocrust. In leaving their old sheath envelope behind when moving into the new soil layer, the microbial sheaths continue to stabilize the older soil layers. This leads to a characteristic soil layering that can be easily observed in soil cross-fractures or even in the fossil record (see Fig. 9.2h). For example, the internal and external morphology of the microbial species tested in McKenna-Neuman et al. (1996) and McKenna-Neuman and Maxwell (1999, 2002) may explain the observed order of resistance. *Trichoderma harzianum* has a robust external structure and internal septa to reinforce the cells. *Absidia corymbifera* has an exterior similar to *Trichoderma harzianum* but lacks the internal septa. *Aureobasidium pullulans*, in contrast, consists of a chain of weakly linked cells. All three fungal biocrusts were thicker than the photoautotrophic biocrusts, all of which had lower resistance to wind erosion.

For lichens and mosses, important factors conferring stability are (1) size of continuous thallus on the surface that prevents wind from touching the soil, (2) ability to withstand abrasion from both chronic and acute events, and (3) depth and extent of anchoring structures, which prevents the organisms from being uprooted. As can be seen, there is a large amount of variation in the factors listed above. However, we do not know the relative importance of these factors. Because many efforts are currently focused on using biocrusts for soil stabilization, further research on which traits are the most important for stabilization is a critical research need.

Figures 16.1a–h and 16.2a–e show photographs of the different dominant phototrophic species important in stabilizing soils. Unicellular green algae



**Fig. 16.1** (a) The unicellular green alga *Bracteacoccus giganteus* is common in biocrusts but produces only a limited amount of slimy sheath material (micrograph courtesy of Darienko and Friedl). (b) Unicellular green biocrust alga *Neochlorosarcina negevensis*, gelatinous sheath stained blue with 0.1% methyl blue (micrograph courtesy of Darienko and Friedl). (c) The filamentous cyanobacterium *Calothrix* sp. occurs in low densities and produces only thin

(Fig. 16.1a, b) and filamentous green algae and cyanobacteria (Fig. 16.1c–f) glue soil particles together (Fig. 16.1g) and can form an almost continuous cover in many ecosystems (Fig. 16.1h). The internal structure of the stabilizing layer can consist of both living and abandoned sheath layers (Fig. 16.2a). Liverworts (Fig. 16.2b), moss (Fig. 16.2c), and lichens (Fig. 16.2d, e) are also important stabilizers, and in fact, as they occur above the actual soil surface, they often offer better protection than cyanobacteria or green algae. Fungi are also critical in stabilizing soils and act similarly to the filamentous cyanobacteria.

### 16.2.3 Developmental Stage Affects Resistance to Soil Loss

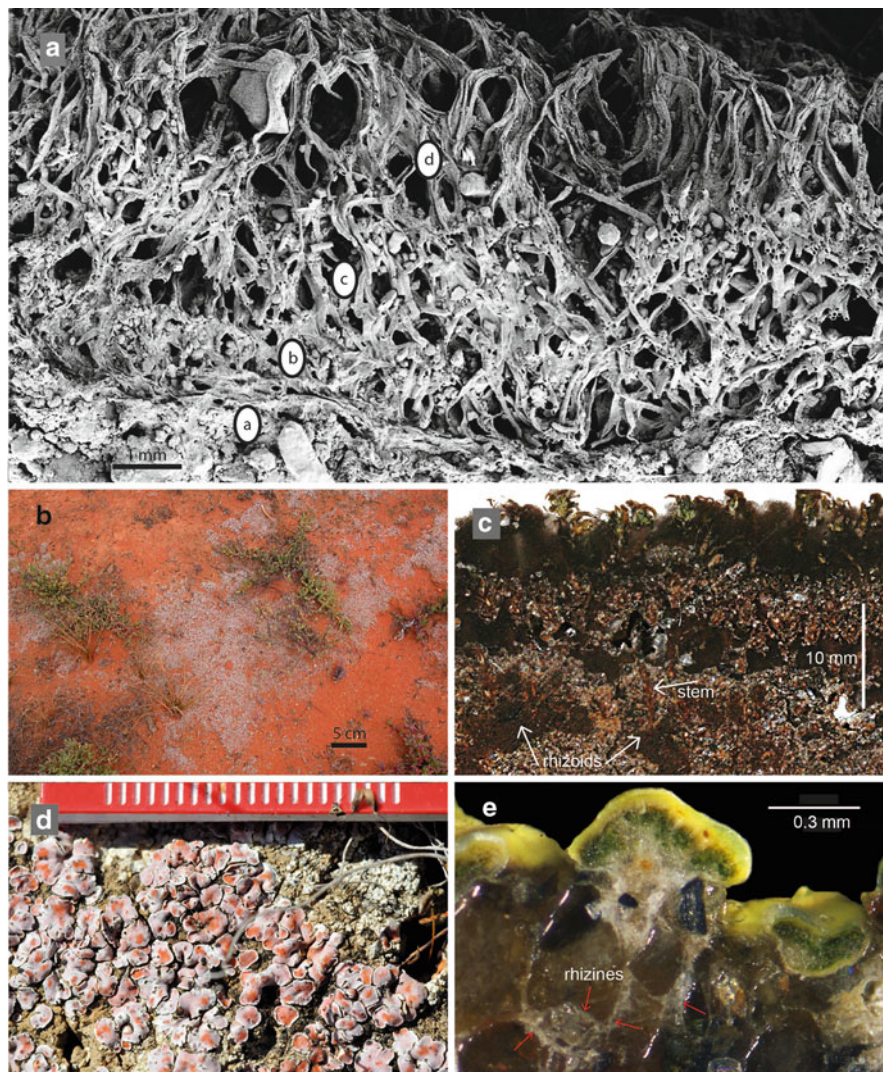
At very low biomass levels, cyanobacterial biocrusts do not confer resistance to wind erosion. In the Mojave Desert of southern CA, USA, a minimum of  $0.01 \text{ mg chl } a \text{ g}^{-1}$  soil was needed to stabilize soils (Belnap et al. 2007). Hu et al. (2002) reported this threshold to be higher at  $0.6 \text{ mg chl } a \text{ g}^{-1}$  soil. Belnap et al. (2014) used regression tree analyses and found that the most important factor predicting TFV was cyanobacterial chlorophyll *a*, with soils containing  $>0.014 \text{ mg g}^{-1}$  soil having twice the stability of those below that value. Belnap et al. (2008) also found a strong relationship between cyanobacterial chlorophyll *a* and soil stability ( $R^2 = 0.77$ ). Unfortunately, we do not have data on the lowest threshold for resistance to water erosion.

Among young biocrusts, there is an exception to the pattern of increasing resistance to erosion with increasing biomass. At a certain point in development when biomass is low, the biocrust organisms have created enough cohesion to hold the soil surface particles together but are insufficiently anchored to the soil to withstand acute stress created by high winds or water. Under these conditions, large cyanobacterial/fungal-bound soil flakes can be seen detaching from the soil surface and blowing or washing away (McKenna-Neuman et al. 1996; McKenna-Neuman and Maxwell 1999, Belnap pers. obs.).

With time, cyanobacterial biomass increases past the stage of the flaking issue and later-successional mosses and lichens colonize, conferring increased resistance to soil erosion as cover and biomass increase [reviewed in Belnap (2003) and Warren (2003a, b)]. Because lichens and mosses actually protrude above and cap

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**Fig 16.1** (continued) gelatinous sheaths. Photo by B. Büdel. **(d)** Filaments of the green alga *Klebsormidium* sp. inside biocrusts with soil particles attached to the sheath. Photo by B. Büdel. **(e)** The filamentous cyanobacterium *Nostoc* cf. *microscopicum* occurs in medium density but produces thick sheaths. Photo by B. Büdel. **(f)** The filamentous cyanobacterium *Microcoleus vaginatus* occurs in large amounts in biocrusts and produces a huge amount of sheath that remain in the substratum even after the trichome left; attached soil particles mark the extent of the sheath. Photo by B. Büdel. **(g)** *Microcoleus vaginatus* filaments with up to  $100 \mu\text{m}$  large soil particles attached to its thick, sticky sheath. Photo by B. Büdel. **(h)** Well-developed cyanobacterial biocrust forming a dense cover in the high European Alps, 2600 m a.s.l. Photo by B. Büdel



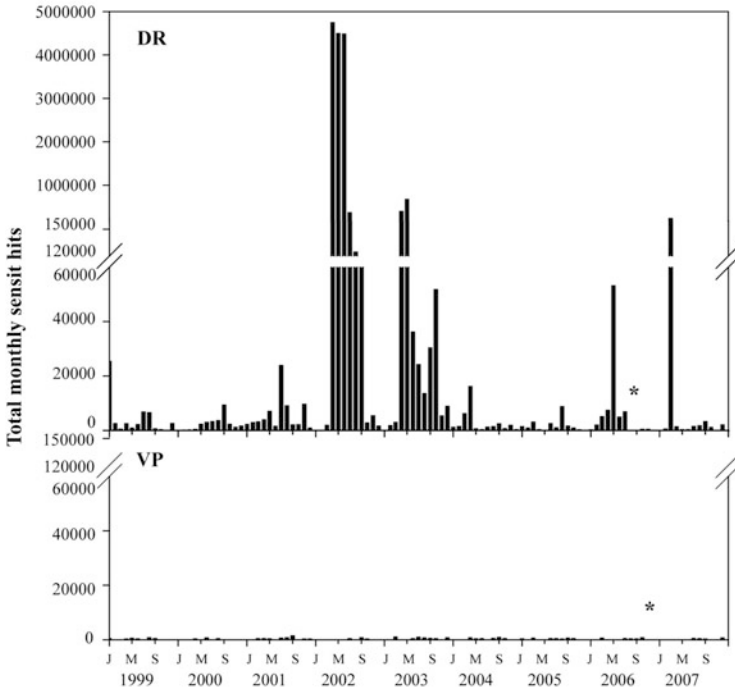
**Fig. 16.2** (a) Crust structure of a *Symplocastrum* cf. *purpurascens*-dominated biocrust. a = basal layer with compressed empty sheaths; b = 2 seasons old layer with empty sheaths; c = new layer with trichomes inside the sheaths. Photo by B. Büdel. (b) Liverwort (*Riccia* sp.)-dominated biocrusts covering large parts of the soil, Western Cape region, South Africa. Photo by B. Büdel. (c) Cross section of a moss-dominated biocrust. The moss covers the soil surface almost completely, with rhizoids (reddish filaments) penetrating several millimeters into the soil. Photo by B. Büdel. (d) Dense biocrust dominated by the green algal lichen *Psora decipiens*, covering the soil surface more or less completely. Photo by B. Büdel. (e) Cross-fracture of a lichen-dominated (*Acarospora gwynnii*) biocrust, with rhizines penetrating the soil surface up to 1 mm. Photo by B. Büdel

the soil surface and add relatively deep (up to 5 cm) anchoring structures, later-successional biocrusts are better able to withstand both the abrasion of soil particles driven by wind and raindrop erosion associated with water erosion than cyanobacterial crusts, regardless of the cyanobacterial biomass (Qin and Zhao 2011; Zhao et al. 2014). In addition, water velocity can be a major factor in determining sediment production in some settings, as slower water carries less sediment and has lower erosive power. The external morphology of biocrusts has a large effect on velocity. In hot deserts and some temperate regions, cyanobacteria smooth and flatten the soil surface, increasing water velocity (Belnap 2006). In contrast, many of the biocrusts found in cool and cold deserts have an extremely roughened soil surface created by freezing, pushing the soils upward and rain differentially eroding downward and this roughened surface greatly slows water velocity. However, the specific interaction of water velocity and biocrust roughness has not been quantified in enough studies to understand its importance. In addition, better developed biocrusts contribute significant amounts of organic carbon to soils via carbon fixation (Lange 2003) and decaying organic matter (Danin and Ganor 1991), both of which contribute to aggregate formation and thus soil stability.

Studies since 2000 have uniformly verified the relationship between the developmental stage of biocrusts and resistance to erosion. Belnap et al. (2009) showed that under natural field conditions in average rainfall years, a site covered with thin cyanobacterial biocrust and annual plants (due to grazing impacts) under average rainfall conditions produced 2.8 times the sediment of a site covered with lichen-moss biocrust and a sparse but perennial grass cover (Fig. 16.3). In drought years, this difference became 5600-fold between the sites. Regression analysis showed that biocrust cover was the most important predictor of site stability (Belnap et al. 2009). Using a wind tunnel in the field, Goossens (2004) reported that well-developed biocrusts better stabilized soils from wind erosion than cyanobacterial biocrusts. Again with a wind tunnel in the field, Belnap et al. (2014) found that the most stable biocrusts were those with lichens and mosses when compared with cyanobacterial biocrusts. Reynolds et al. (2001) showed that moss-lichen biocrusts collect and retain dust for multiple decades. Using a wind erosion model, Munson et al. (2011a, b) showed that well-developed moss-lichen biocrusts could prevent any soil loss from wind erosion even in the absence of all vascular plants.

Well-developed biocrusts similarly decrease or prevent water erosion. Using a rain simulator, Eldridge and Leys (2003) found soil erosion decreased by almost two orders of magnitude as biocrust cover increased from 0 to 100 % and Bowker et al. (2008) found that cyanobacterial biomass was a moderate to excellent predictor of soil stability ( $R^2 = 0.21-0.75$ ), depending on soil type. Barger et al. (2006), using rainfall simulation, found that erosion was five times higher from soils covered by low-biomass (light) crusts than from soils covered by better developed (dark) biocrusts. At the small watershed scale (~1 ha), silt fences were used to collect natural sediment off the adjacent biocrusted and uncrusted surfaces (Jayne Belnap, unpublished). On clay and sandy soils, two and five times as much sediment, respectively, was collected from the uncrusted compared to biocrusted soils. Some work in temperate regions has been done as well. Knapen et al. (2007)

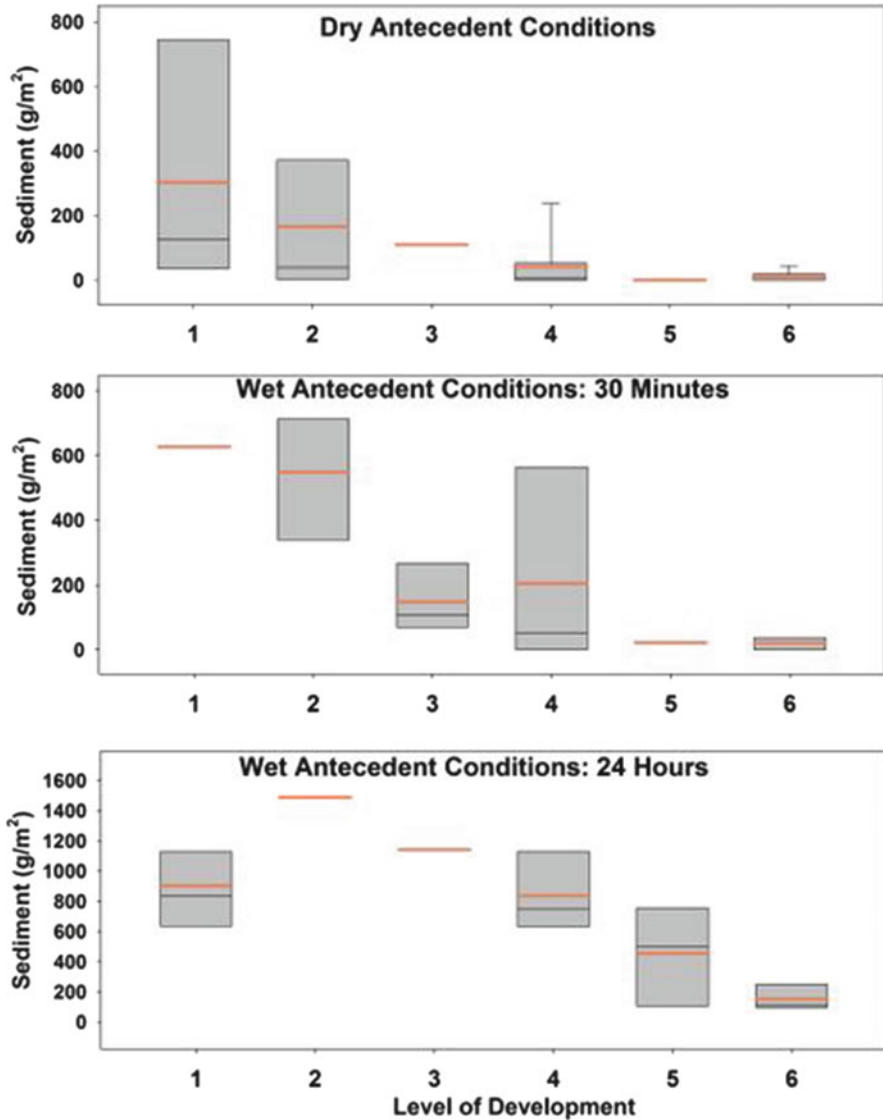




**Fig. 16.3** Movement of soil particles detected by SENSITs (SENSIT probes protrude above the soil surface  $\sim 15$  cm, counting the number of saltating particles upon impact, thus estimating the amount of sediment movement) in an area (DR) dominated by cyanobacterial biocrusts and a nearby one (VP) dominated by moss-lichen biocrusts. Sediment movement was always greater at the DR site compared to VP. However, this difference was greatly exacerbated during the exceptionally dry months of May–Sept 2002 and 2003. During this time, sediment movement was greatly increased at the DR site, whereas little change was noted where moss-lichen biocrusts covered the soils [Adapted from Belnap et al. (2009)]

investigated the effect of biocrusts on croplands in central Belgium and found that they decreased soil erosion. At the large watershed scale, Cantón et al. (2011) found that bare soil or physical crusts produce up to  $20\times$  more sediment as biocrusted soils on marl, mica schist, and limestone-derived soils. Gaskin and Gardner (2001) found that biocrusts reduced soil losses by up to 50 % compared with a maize crop devoid of groundcover.

Belnap et al. (2008) developed a level of development (LOD) that visually divided biocrusts into six classes of development, with 0 being bare soil and 6 being a well-developed lichen-moss biocrust. Using a rain simulator on biocrusts present in plant-free interspaces between *Coleogyne ramosissima* shrubs and storm sizes equivalent to  $>500$  year events, mean sediment loss from early cyanobacterial crusts (LOD 1) was  $\sim 300$  g m $^{-2}$ , whereas there was almost no sediment produced from LOD 6 biocrusts (Fig. 16.4, upper panel; Belnap et al. 2012). Data from this study were used to parameterize the Rangeland Hydrology and Erosion Model



**Fig. 16.4** Box plots of sediment production for each biocrust LOD class, with 0 being bare soil and 6 being a well-developed lichen-moss biocrust. The ends of the boxes define the 25th and 75th percentile, the error bars define the 10th and 90th percentiles, the *black line* is the median, and the *orange line* is the mean. Where *error bars* or *boxes* are lacking, there were only 2–3 replicates. Experimental plots were located in plant-free interspaces between *Coleogyne ramosissima* shrubs [Adapted from Belnap et al. (2012)]

(RHEM), and model runs showed that sediment production was much more sensitive to changes in slope length and gradient when biocrusts were in their least developed condition (LOD 1 and 2). Thresholds of slope length (10 m) and gradient (10 %) were observed, beyond which erosion increased sharply. With more

developed biocrusts (LOD 4–6), sediment production was relatively insensitive to changes in either slope length or gradient. In addition, model runs showed runoff, and thus sediment production, occurred with only 10 mm of rain in LOD 1 biocrusts under dry conditions, whereas events of ~40 mm were required for runoff and sediment production in LOD 2–6 biocrusts. As storms of this size are extremely rare in most deserts, these better developed biocrusts offer almost complete erosion resistance. Chaudhary et al. (2009) demonstrated that biocrust cover had over three times the explanatory power of any other variable measured ( $r^2 = 0.60$ ).

#### ***16.2.4 Antecedent Moisture Affects Resistance to Soil Loss***

Antecedent moisture also plays a substantial role in determining how much eroded sediment a given rain event will produce (Fig. 16.4, middle and lower panels; Belnap et al. 2012). When a rainfall simulator was used to apply events to dry soils, LOD 1–2 biocrusts produced some sediment, whereas LOD 4–6 biocrusts were stable. However, when soils were pre-wetted for 30 min, the mean sediment produced by LOD 1–4 biocrusts was up to twice that when the rain event was applied to dry soil. Biocrusts with LOD 5 and 6 remained stable. When rain events were applied to biocrusts that had been pre-wetted for 24 h, the increase in sediment production was dramatic: for biocrusts with LOD 1–5, sediment production increased by up to 11-fold, with biocrusts of LOD 6 remaining stable. Thus antecedent moisture not only resulted in more sediment being produced, but the longer the soils were moist, the more likely better developed biocrusts were to produce substantial amounts of sediment.

### **16.3 Disturbance to Biocrusts Reduces Resistance to Soil Loss**

All studies show an increase in both wind and water erosion when biocrusts are disturbed, as disturbance essentially reduces biomass and developmental stage of the biocrusts. Early studies with wind tunnels showed a four- to fivefold increase in sediment production when a biocrusted surface is disturbed [reviewed in Belnap (2003)]. These findings have been corroborated with later studies. Eldridge and Leys (2003), using a wind tunnel, determined that at least 20 % cover is required to keep sediment transport below an erosion control target of  $5 \text{ g}^{-1} \text{ s}^{-1}$  for a  $65 \text{ km h}^{-1}$  wind at 10 m height. Neff et al. (2008) showed that dust input to high-elevation lakes has increased 5–8 times during the period when large-scale agriculture, including live-stock, appeared in the Western USA. Although we cannot know the degree to which biocrust disruption contributed to this spike in dust production, it is likely significant, as most undisturbed soils in this region are covered and stabilized by biocrusts. Wind

tunnel work by Belnap (in Field et al. 2010) shows that across a wide range of soil textures, disturbed biocrusts produce up to  $400\times$  the sediment of undisturbed biocrusts. In China, no sediment was produced from sandy biocrusted soils at a wind velocity of  $25\text{ m s}^{-1}$  (Zhang et al. 2008). However, sediment production rates were 46, 21, and 17 times higher on bare soils than biocrusted soils at wind speeds of 18, 22, and  $25\text{ m s}^{-1}$ , respectively. In addition, TFV for an undisturbed surface was  $19\text{ m s}^{-1}$  higher than a disturbed biocrust.

## 16.4 Nutrient Loss with Erosion

Nutrients are also lost with sediment movement. In southern New Mexico, USA, wind erosion after disturbance of the soil surface removed up to 25 % of total organic carbon and nitrogen from the top 5 cm of soil in four windy seasons (Li et al. 2007). Because carbon and nitrogen are the first to mobilize and other cations (e.g., potassium, sodium) are less likely to move, the spatial heterogeneity of nutrients is altered, which can then affect plants and biogeochemical cycling in the soil (Li et al. 2008). Another study in southern Utah, USA, showed that wind erosion had depleted silt by 38–43 %, soil carbon and nitrogen by 60–70 %, and other essential nutrients (magnesium, sodium, phosphorus) by 14–51 % (Neff et al. 2005).

Using a rain simulator, Barger et al. (2006) showed that there was up to a fivefold higher loss of sediment-bound carbon and nitrogen (N) from plots covered by low-biomass biocrusts compared to plots covered by high-biomass biocrusts. Total N loss from dark crusts (dissolved plus sediment-bound) was an order of magnitude lower than light crusts (dark =  $0.06\text{ g N m}^{-2}$ , light =  $0.63\text{ g N m}^{-2}$ ). Jayne Belnap (unpublished) found that soils collected by silt fences from uncrusted sandy sites contained more phosphorus (11 vs. 4 ppm), potassium (K; 79 vs. 48 ppm), N (344 vs. 104), and silt (19 vs. 9 %) compared to the biocrusted soils. At the clay sites, uncrusted soils lost significantly more K (286 vs. 163 ppm) and silt (33 vs. 21 %) than the biocrusted sites. Kidron (2001) showed that eroded soils may be enriched in organic matter as well, with 0.3–0.4 % being measured in collected sediment versus  $\leq 0.1\%$  found at the source.

## 16.5 Soil Movement at the Local to Global Scale

Soil movement has implications for nutrient and water cycles at the local, regional, and global scales. Where biocrusts are disturbed, or in regions where hot, dry conditions keep them at a low developmental stage (e.g., hyperarid deserts); they offer little protection from soil erosion. At the local scale, this has several implications. First, far-traveled fine dust falls more or less equally across the landscape. If biocrusts are lacking, this dust is redistributed by water downslope or by wind to

nearby obstructions, resulting in a heterogeneous distribution of nutrients and soil particle sizes (Shachak and Lovett 1998; Reynolds et al. 2001). In addition, movement by wind and water can also deposit the soil in nearby stream channels, where stream waters export the sediment from the system (Belnap et al. 2011). Particles suspended by the wind can also be exported from the system. This results in soil fertility being reduced locally, as discussed in Sect. 16.4, and sediment entering the water reduces its quality locally and regionally. Dust particles are deposited on the snowpack of nearby mountains, decreasing albedo and hastening snow melt. This exposes soils and allows plants to germinate earlier in the spring, increasing both evaporative and transpiration losses to the atmosphere. This can result in substantially less overall water entering small to large rivers and aquifers and thus lowering water quality as well (Painter et al. 2010).

## 16.6 Future Research

Despite the uniformity in studies finding that biocrusts reduce soil movement by wind or water, we still have limited understanding in the specifics of how biocrusts stabilize soils. Only a handful of studies have evaluated the relative ability of individual species and many others remain to be evaluated. We also need to test suites of species. Once this is done, we need a better understanding of why some individual or combinations of species are better than others. For example, we assume that the amount of exo-polysaccharides a species exudes is important, but we have little information on the circumstances under which this is true, how much is enough, or under what circumstances exo-polysaccharides are produced. This understanding will become increasingly important as biocrust inoculants are increasingly used to stabilize disturbed lands and the composition of the inoculant needs to be decided. This information could also inform whether artificial products (e.g., polyacrylamide gels to substitute for exo-polysaccharides) might augment stabilization efforts.

As later stages of biocrust development better stabilize soils than earlier stages, we also need a better understanding of growth rates for different biocrust species, both under current and future climate conditions. These are only a few examples of further studies that can help elucidate how biocrusts stabilize soils.

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