Geomorphic controls of biological soil crust distribution, Mojave Desert (USA)

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Abstract

Biological soil crusts (BSCs) are vital features of arid regions. These crusts form living skin that mitigates erosion, influences soil fertility, manages soil moisture/temperature, and prevents desertification. BSCs are fragile resources, easily destroyed by physical disturbances and potentially impacted by climate change. Our investigation employs a novel, interdisciplinary approach to investigate BSC biotic potential (bridging gaps among biology, ecology, soils, hydrology, statistics, chemistry, geomorphology, remote sensing, and GIS).

Our study documents important links among BSCs, soils, geomorphology, and land stability. Results indicate geomorphic stability and dust influx impact BSC composition and development. Soil stability ultimately controls biotic potential of cyanobacterial versus moss-lichen crust; however, dust influences both crust types through texturally enhanced water-holding capacity and increased soil fertility. Soil chemistry of moss-lichen substrates exhibit a potential dust signature, with elevated Ca, K, Mg, B, Fe, Ni, Co, Mn, Cl, and EC. While results indicate inherent geomorphic stability controls BSC development, we suggest BSCs enhance their propagation through dust capture and erosion mitigation. These soil-geomorphic relationships present insight into arid landscape evolution, providing tools to improve BSC mapping and land management.

Key Words

biological soil crust, ecology, pedogenesis, geomorphology, erosion, dust

Introduction

Biological soil crusts (BSCs) provide critical ecosystem services in deserts around the world. These crusts are microbial complexes that fuse around soil particles to create a living, protective skin. BSCs fill plant interspaces, covering up to 70 percent of the landscape (Friedmann and Galun 1974; Belnap 1994; Belnap 1995). BSCs improve soil productivity and desertification resistance by impacting soil erosion/deposition, water movement, energy balances, landscape stability, soil fertility, and plant community establishment (Eldridge and Greene 1994; Belnap 1995; Belnap et al. 2001).

BSCs are easily destroyed by physical impacts (off-road vehicles, hiking, grazing, etc.), making them highly sensitive to land use changes (Belnap 1995). BSCs present unique challenges to land managers (Belnap et al., 2001). The organisms' size and patchy growth make large-scale mapping and modelling impractical (Eldridge and Rosentreter 1999; Belnap et al. 2001). Furthermore, the ecological controls of BSC distribution are poorly constrained, particularly within the Mojave Desert (USA). In this study, we investigated the complex interrelationships between BSCs and soil-geomorphology to address ecological questions and mapping challenges.

Methods

Soil-geomorphology data were compared and contrasted with BSC data. Eleven BSC units (plus sandstone/limestone outcrops and roads) were delineated and described according to species composition and surface characteristics. Ten geomorphic surfaces were mapped according to topography, elevation, depositional environment, and soil profile development (as seen along washes). Units included alluvium (10 units with ages ranging from Late Miocene/Earliest Pleistocene to recent Holocene), active sand sheets, colluvial slopes, limestone, sandstone, and roads. A soils map was derived through correlation of USDA Official Soil Series with geomorphic units (Soil Survey Staff 2007). Seven soil units were successfully correlated with four series (Arizo, Bluepoint, Ferrogold, Irongold)(Soil Survey Staff 2007). Uncorrelated soils were named according to their taxonomy (Soil Survey Staff, 2006). Soil and geomorphic maps were overlayed with the BSC map for percent overlap between map units (ESRI Arc GIS 9.2 Desktop; Microsoft Excel). Transect data were collected from 36 plots to quantify soil cover and environmental characteristics within BSC map units. BSC samples were microscopically analysed to confirm genera identification.

Surface soils were sampled and analysed for soil texture, pH, EC, total C, inorganic C, organic C, total N, NO_3, total S, SO_4, Cl, PO_4, K, Ca, Fe, Mg, B, Mn, Cu, Zn, Mo, and Ni. Data were statistically analysed with Pearson product-moment correlation coefficients (Microsoft Excel) and multivariate statistical techniques including Nonmetric Multidimensional Scaling (NMS) and Multiresponse Permutation Procedures (MRPP) (MJM Software 2006).

Results

Soils & Geomorphology

Overlays between BSCs and soil/geomorphic maps revealed high correlation between cyanobacterial crusts and sand sheets. The cyanobacterial-dominated BSC unit had 66% overlap with geomorphic unit "Qe" and soil series "Bluepoint". These sand sheet units are >1m deep with negligible soil development. Moss-lichen crusts were correlated with mid-Holocene alluvial soils. Pinnacled BSC units overlapped 57-59% with geomorphic units "Qay_1"and "Qay_2" and overlapped 57-59% with "Arizo" soil series. These surfaces have sandy-skeletal soils with Stage I-II carbonate morphology, incipient Av horizon development (within moss-lichen pinnacles), and faint bar and swale morphology. Transect data yielded similar results, with high-moss lichen cover on Arizo soils and geomorphic surfaces $Qay_1$and Qay_2; while high cyanobacterial cover was found on Bluepoint soils and Qe geomorphic units.

Ecology

Pearson product-moment correlations of interspace cover versus environmental characteristics are summarized in Table 1. Multiple environmental variables were overlayed on a three-dimensional NMS ordination. Environmental factors accounted for 92% of the variability found in interspace BSC distribution.

Interspace Characteristics	% Interspace Cover		
	Cyano-bacteria	Moss & Lichen	Total BSCs
% Limestone	-0.49	-0.47	-0.80
Rock Cover	-0.57	-0.43	-0.83
% Bare	0.38	-0.39	-0.08
% *Bromus Rubens*	-0.21	0.27	0.09
Pleuraphis rigida	0.61	-0.22	0.25
Hymenoclea salsola	-0.26	-0.11	-0.30
Larrea Tridentata	0.51	0.01	0.39
Eriogonum fasciculatum	-0.06	0.29	0.22
Max. Pinnacle Ht.	-0.15	0.73	0.55
% Clay	0.33	-0.40	-0.12
% Silt	-0.29	-0.01	-0.23
% VF Sand	-0.20	0.38	0.19
% F Sand	0.34	0.00	0.26
K	-0.22	0.55	0.34
Mg	-0.06	0.55	0.46
Ca	-0.41	0.61	0.26
Cl	0.16	0.19	0.30
SO_4	-0.21	0.07	-0.09

Interspace Characteristics	% Interspace Cover		
	Cyano-bacteria	Moss & Lichen	Total BSCs
NO_3	-0.16	-.010	-.021
Mn	0.12	0.30	0.37
Fe	-0.29	0.47	0.22
Ni	-0.25	0.48	0.25
Cu	0.23	-0.53	-0.32
Co	0.06	0.30	0.33
B	-0.35	0.61	0.30
Mo	0.33	-0.15	0.12
Available P	-0.41	0.18	-0.15
pH	0.03	-0.40	-0.35
EC	-0.30	0.55	0.28
Total C	-0.57	-0.07	-0.50
Inorg. C	-0.52	-0.20	-0.58
Org. C	-0.44	0.05	-0.29
Total N	-0.43	0.26	-0.08
Total S	-0.12	0.27	0.16
C:N Ratio	-0.39	-0.33	-0.60
Carbonate	-0.52	-0.20	-0.58

🟥 $R^2 > 0.39$

🟩 $R^2 < -0.39$

🟦 $R^2 > 0.19$

🟧 $R^2 < -0.19$

Table 1. Pearson's product-moment correlation coefficients (R^2) are summarized for selected interspace characteristics. Results are reported as correlations between percent interspace cover and other characteristics.

An NMS plot (Figure 1) illustrates select correlations among biological and environmental variables. NMS analyses show lichen, moss, and grass (invasive *Bromus rubens*) are all positively associated with K, B, Ca, EC, Fe, very fine sand, and pinnacle relief and are negatively associated with cyanobacteria cover and bare soil. BSC cover classes (moss, lichen, and cyanobacteria) are negatively associated with limestone cover, NO_3, C:N ratios, inorganic carbon (carbonate), and Cu.

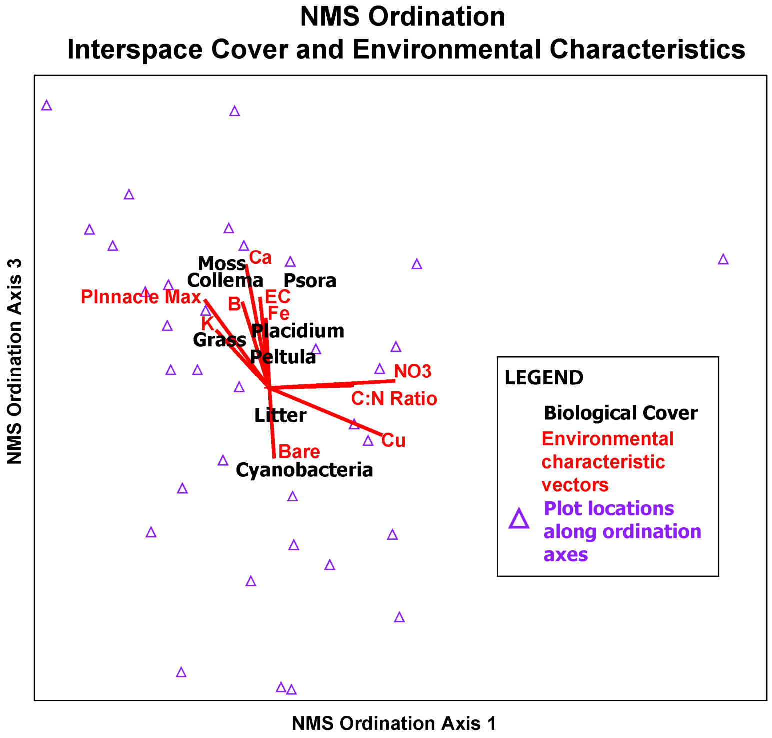

Figure 1. A 3-D NMS ordination of soil interspace shows relationships among biological variables (2-D shown). Strongly associated species (in black) are shown closer together. Plots (triangles) are graphed closest to their compositional species. Red lines (vectors) point to species with which they are strongly associated.

MRPP analyses tested the effectiveness of soil, geomorphic, and BSC map units in grouping interspace cover. MRPP results are reported as association values (A). When A=1, group members are identical; and when A=0, group members are not similar (McCune and Grace, 2002). McCune and Grace (2002) state A>0.3 are high values for ecological data sets. MRPP results showed the following: soil map units (A=0.29; p=0.00000875), BSC map units (A=0.52; p=0.00000000), geomorphic map units (A=0.35; p=0.00000657).

Discussion

Soils and Geomorphology

Results indicate a strong relationship between soil-geomorphology and BSC distribution. Cyanobacteria crusts are most prominent on surfaces of high geomorphic instability, namely sand sheets. Instability only permits establishment of mobile BSC organisms, such as *Microcoleus sp*. Moss-lichen crusts are most extensive on stable surfaces with maximum dust influx, specifically mid-Holocene surfaces. These surfaces are elevated from active alluvial processes, but have increased surface roughness compared to older geomorphic surfaces and therefore receive higher rates of dust accumulation (McFadden et al., 1987). Dust enhances the water-holding capacity and fertility of the soil, thereby improving BSC growth and development. Moss-lichen BSCs may amplify the dust capture along mid-Holocene surfaces by increasing microtopography and decreasing erosional losses. These positive feedback mechanisms may allow BSCs to effectively “engineer” their habitat to improve propagation. MRPP analyses suggest soil and geomorphic maps are effective predictors of BSC distribution, greatly enhancing ecological crust models.

Ecology

Results show BSC distribution is strongly influenced by dust-related texture and chemistry changes. Cyanobacterial crusts are highly correlated with clay volumes, perhaps because their sticky sheaths capture the finest dust fraction. Microscopic observations of cyanobacteria confirmed presence of soil fines in extracellular polysaccharides. Moss-lichen crusts are associated with the very fine sands, likely derived from the coarser dust fraction. In both cases, dust influx increases the concentration of fine particles, enhancing soil water-holding capacity, soil fertility, and BSC propagation.

Soil chemistry of moss-lichen substrates suggests an influence of dust, with elevated concentrations of Ca, K, Mg, B, Fe, Ni, Co, Mn, Cl, and high EC. Depending on the source area, dust may contain high levels of macro- and micronutrients beneficial to BSC growth. In contrast, Cu is negatively correlated with moss-lichen cover. While it is unclear why Cu relationships differ from those of other metallic ions, we hypothesize that some organic chelator (associated with BSCs) may increase its mobility. Alternatively, BSC organisms may be hyperaccumulating copper, but one would expect turnover to offset uptake.

Nitrate (NO_3) is negatively correlated with moss-lichen crusts, with low nitrate levels under moss-lichen relative to soil below rock fragments. Organic matter from pinnacled BSCs may increase the time soils remain moist. If so, net denitrification would be higher below moss-lichen BSCs, explaining nitrate losses. Likewise, extensive rock cover could increase runoff and decrease infiltration, lowering soil moisture and net denitrification relative to soils under BSCs. The source of nitrate is likely salt-rich dust fall, as nitrate, sulfate, and chloride are all positively correlated with each other. Total nitrogen is positively correlated with moss-lichen cover. BSC tissues found in soil samples may account for additional nitrogen. The nitrogen budget of this system warrants further investigation.

Conclusions

This study illustrates the importance of soil-geomorphic characteristics in controlling BSC distribution. While geomorphic processes largely control surface dynamics, our results suggest BSCs also play an active role in soil stabilization and dust trapping. Dust accumulation strongly influences surface soil chemistry with elevated concentrations of clays/fine sands, Ca, K, Mg, B, Fe, Ni, Co, Mn, Cl and high EC associated with moss-lichen substrates. In contrast, NO_3 and Cu are both negatively correlated with BSCs. Moss-lichen crusts could have greater soil moisture leading to higher net denitrification. Organic chelators associated with moss and lichen could lead to increased Cu mobility. These important connections between soil-geomorphic characteristics and crusts highlight the potential use of surficial mapping in BSC management. While current efforts examine moisture availability impacts in crust growth, continued research will explore the complex role of BSCs in soil landscape evolution through time.

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