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Geomorphic controls on biological soil crust distribution: A conceptual model from the Mojave Desert (USA)

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ABSTRACT

Biological soil crusts (BSCs) are bio-sedimentary features that play critical geomorphic and ecological roles in arid environments. Extensive mapping, surface characterization, GIS overlays, and statistical analyses explored relationships among BSCs, geomorphology, and soil characteristics in a portion of the Mojave Desert (USA). These results were used to develop a conceptual model that explains the spatial distribution of BSCs. In this model, geologic and geomorphic processes control the ratio of fine sand to rocks, which constrains the development of three surface cover types and biogeomorphic feedbacks across intermontane basins. (1) Cyanobacteria crusts grow where abundant fine sand and negligible rocks form saltating sand sheets. Cyanobacteria facilitate moderate sand sheet activity that reduces growth potential of mosses and lichens. (2) Extensive tall moss–lichen pinnacled crusts are favored on early to late Holocene surfaces composed of mixed rock and fine sand. Moss–lichen crusts induce a dust capture feedback mechanism that promotes further crust propagation and forms biologically-mediated vesicular (Av) horizons. The presence of thick biogenic vesicular horizons supports the interpretation that BSCs are long-lived surface features. (3) Low to moderate density moss–lichen crusts grow on early Holocene and older geomorphic surfaces that display high rock cover and negligible surficial fine sand. Desert pavement processes and abiotic vesicular horizon formation dominate these surfaces and minimize bioturbation potential. The biogeomorphic interactions that sustain these three surface cover trajectories support unique biological communities and soil conditions, thereby sustaining ecological stability. The proposed conceptual model helps predict BSC distribution within intermontane basins to identify biologically sensitive areas, set reference conditions for ecological restoration, and potentially enhance arid landscape models, as scientists address impacts of climate change and anthropogenic disturbances.

1. Introduction

Biological soil crusts (BSCs) are complex matrices of soil particles, cyanobacteria, lichens, mosses, algae, microfungi, and bacteria (Friedmann and Galun, 1974; Belnap and Gardner, 1993; Williams et al., 2012). BSCs provide crucial soil cover in arid and semi-arid landscapes. Biotic structures grow around surface sediments, fusing into a desert skin that mitigates erosion (McKenna Neuman et al., 1996) and provides ecosystem services including soil nutrient inputs (Kleiner and Harper, 1977; Evans and Belnap, 1999), regulation of soil moisture and temperature (Belnap, 1995, 2006), enhancement of landscape stability (Canton et al., 2003; Thomas and Dougill, 2007), and interactions with vascular plant communities (DeFalco et al., 2001; Escudero et al., 2007). The ecological impacts of BSCs are potentially enormous, as crusts can comprise up to 70 percent of the living soil cover in arid landscapes (Belnap, 1994), and commonly fill shrub interspaces, which are the exposed surfaces between vascular plants.

BSCs vary widely in biotic composition and surface morphology (Fig. 1). Smooth, early succession crusts are dominated by filamentous cyanobacteria (Fig. 1B) (Belnap, 2001). Once soils are stabilized, mosses and lichens colonize the surface with cyanobacteria to form short moss–lichen crusts with rolling surface morphologies and less than 2 cm of vertical relief (Fig. 1E) (Belnap, 2001; Williams et al., 2012). Eventually, tall moss–lichen pinnacled crusts develop, which display rougher surfaces and up to 5 cm of vertical relief (Fig. 1D) (Williams et al., 2012).

A number of models have been developed to predict the distribution of crust types throughout many of the world's arid and semi-arid regions (Eldridge and Greene, 1994; Kidron et al., 2000; Ponzetti and McCune, 2001; Belnap et al., 2006; Bowker et al., 2006; Thomas and Dougill, 2006; Bowker, 2007; Bowker and Belnap, 2008; Rivera-Aguilar

Abbreviations: BSCs, biological soil crusts; OHVs, off-highway vehicles; MRPP, multi-response permutation procedures.

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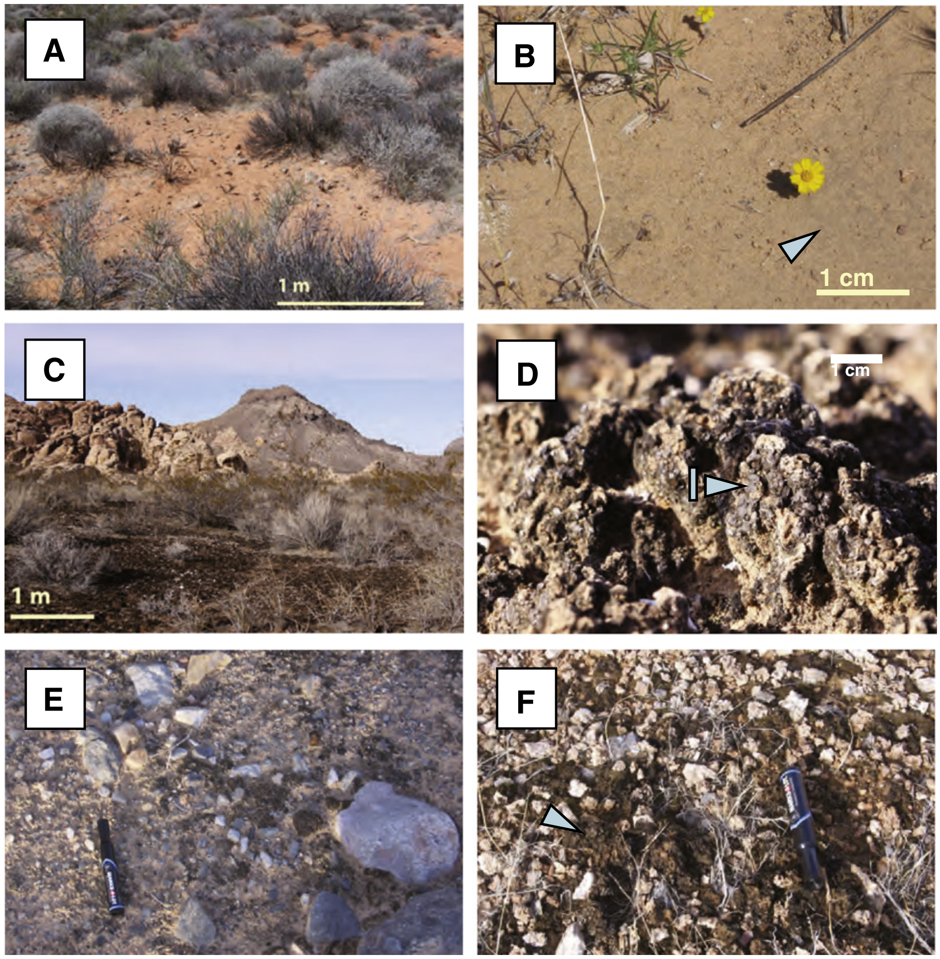

Fig. 1. (A) High density cyanobacteria-bare crusts (BSC map unit CB.1). (B) Cyanobacteria crusts display slightly darkened surfaces (arrow). (C) High density, tall moss–lichen pinnacled crusts (BSC map unit ML.1). (D) Squamulose lichens (l) dominate a tall pinnacle. (E) Moderate density, short moss–lichen crusts (BSC map unit CB.2, marker for scale). (F) Scattered, moderate density tall moss–lichen pinnacled crusts (BSC map unit S.2, marker for scale). See Tables 1and S2 for BSC map unit descriptions. (Images adapted from Williams et al., 2012.)

et al., 2009). To date, however, no predictive models exist for Mojave Desert crusts, and only a few studies from any environment have considered the interaction of BSCs with geomorphic or physical soil-forming processes that could strongly influence crust establishment and propagation (Brostoff, 2002; Thomas and Dougill, 2007; Wang et al., 2007; Bowker and Belnap, 2008; Lazaro et al., 2008; Li et al., 2010). For example, surface stability (Bowker and Belnap, 2008; Rivera-Aguilar et al., 2009), topography (Lazaro et al., 2008; Li et al., 2010), rock cover (Kaltenecker et al., 1999; Quade, 2001), soil texture and mineralogy (Bowker and Belnap, 2008; Rivera-Aguilar et al., 2009), and hydrological dynamics (Kidron et al., 2000; Bowker et al., 2010) are key factors influencing BSC distribution and species composition. These factors commonly vary as a function of soil-geomorphology, particularly within the intermontane basins of the Mojave Desert (Peterson, 1981; Young et al., 2004; Soil Survey Staff, 2007; Robins et al., 2009).

The objectives of this study were (1) to investigate the relationships among geomorphology, soil characteristics, and BSC distribution in the Mojave Desert; (2) to understand the landscape feedback mechanisms that control geomorphic stability, pedogenesis, and BSC development within the region; and (3) to use soil-geomorphic relationships to predict BSC distribution for land management applications.

2. Background and geologic setting

The study site lies within the Hidden Valley Area of Critical Environmental Concern, inside the Muddy Mountains Wilderness in the Mojave Desert of southern Nevada, USA (Fig. 2) at 36°20′N and 114°42′W. The area is ideal for studying BSC-soil-geomorphic interactions as the valley contains well-developed and variable BSCs, numerous geomorphic surfaces, and common Mojave Desert soil types and plant communities (Soil Survey Staff, 2007). Mean annual temperature is 27 °C, and mean annual precipitation is 114 mm (Gorelow and Skrbac, 2005). Precipitation is greatest from January to March when average highs range from 14 to 21 °C, but precipitation also occurs from July to August, when average highs are 39–40 °C (Gorelow and Skrbac, 2005).

Hidden Valley is a semi-enclosed basin that displays typical intermontane basin geomorphology (Peterson, 1981). The valley lies at 1000 m elevation and is surrounded by mountains comprised of carbonate and sandstone bedrock that rise up to 1642 m. These mountains formed during Sevier-age thrusting when Paleozoic carbonates were thrust eastward over younger Jurassic Aztec Sandstone along the Muddy Mountain Thrust Fault (Beard et al., 2007). Erosion of the upper plate of the thrust created a structural window that now exposes the underlying sandstone bedrock across the valley floor.

Off-highway vehicles (OHVs) have been prohibited since the area was designated a Federal Wilderness in 2002. Hidden Valley was previously grazed, but the trampling effects of livestock on the area's BSCs are unknown. Despite apparent disturbance to the area, Hidden Valley's crusts have remained relatively pristine compared to other Mojave Desert locations. As Hidden Valley becomes increasingly popular to sightseers in the Las Vegas metropolitan area, off-trail foot traffic and illegal OHV use are becoming significant management concerns.